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A DECIMAL CLASSIFICATION SYSTEM FOR GEOPHYSICAL EXPLORATION*

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Need for Classifying Geophysical[1] Material

It is quite probable that many members of this Society, particularly those with reasonably permanent headquarters, have started to collect geophysical data of some kind or other. If one keeps adding to such a collection over a period of years, the necessity arises sooner or later to classify this material in some way. The writer's own collection, started some twenty-two years ago, would be of little value to him or to anybody else unless it were arranged in systematic form. It is very annoying not to be able to produce a certain article or data although one remembers perfectly well having seen and filed it. Without an orderly classification system, much time is lost searching for it, and needless expense is often incurred in duplicating material already in the files.

If a classification system is desirable for the files of an individual, it becomes almost indispensable for organizations in which a number of individuals contribute to the accumulation of all kinds of data. There are a number of geophysical organizations in which extensive research is carried on continuously; owing to the rapidly changing picture in geophysical exploration, such research will rarely be concerned with one method only. In many instances, it has happened that an abandoned research project has been resumed several years later due to developments in a parallel line of technology. There is ample reason, therefore, why a research organization should preserve and file its data in orderly form, since duplication would turn out to be a very costly procedure.

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[1] See footnote 4.

The same is true, though to a lesser extent, of the operating companies and the operating departments of oil, mining and consulting companies. As far as maps and reports are concerned, it is frequently sufficient to file them by area, locality, client, or order number, and a methodical classification system is not required. However, where operating departments keep track of technical data in connection with instrument operation, transportation problems, legal phases, and cost accounting (all of which vary to a certain extent with the method at hand), it is expedient for them to arrange this material in a systematic manner.

The greatest benefit from a systematic classification is likely to arise in the arrangement of geophysical material in the libraries of oil, mining, and consulting companies, research institutions, universities, and technical schools. At present, there is no uniformity relative to the position of Geophysical Exploration in the accepted classification systems. A superficial examination of the placement of our subject in but a few libraries brought forth no less than four major and several minor categories of classification. One library may classify Geophysical Exploration under Mining Engineering, another under Geology, a third under Physics, and a fourth under Geodesy, with a good chance of having in another instance the subject completely broken up and assigned to various fields of Physics, such as Electricity, Magnetism, Acoustics, etc.

In a comparatively few years, Geophysical Exploration has risen to a prominent industry, involving an annual expenditure variously estimated at between twenty and twenty-five million dollars. Hence, there is ample justification for assigning this subject a more prominent place among the accepted classification systems than it occupies at present and for working out a system which is sufficiently detailed and flexible to take care of the present and future requirements of the industry.

Classification Systems Available

Probably the simplest and most logical way of subdividing the field of Geophysical Exploration would be to assign the main divisions to the established methods, such as gravimetric, magnetic, seismic, electric, etc. These are, indeed, the main divisions that have been established for the classification discussed herein. The question then arises as to the best manner of designating these groups. Two methods are usually employed for this purpose, one using alphabetical letters,

and the other numerals. A numerical system is preferable since it offers the possibility of arranging the subjects in a decimal pattern. Another advantage of the decimal system is that certain digits can be assigned a definite significance in recurrent groups. This is particularly useful in connection with Geophysical Exploration where recurrent groups are exemplified by such topics as historical development, physical rock properties, instruments and methods, results, statistics, and so forth.

In connection with the decimal classification, the question arises whether to employ an independent, self-contained system, or whether to fit the geophysical classification in with some other, already existing, system. A good example of a completely independent system is that proposed by Uren.[2] The Uren system provides for 1000 topics which are subdivided into 10 main groups in such manner that the group from 000 to 100 represents general data, that from 100 to 200 the geographic distribution of fields and data pertaining thereto, that from 200 to 300 physical and chemical properties of petroleum, that from 300 to 400 exploration methods, and so forth. In the last group, we find geophysical equipment listed as topic 306 under the heading of "general references," whereas geophysical methods are listed as topic 368 under the general heading of "geological surveys." This division of our subject into equipment on one hand and methods on the other is somewhat unfortunate. It would leave many users in doubt where to file geophysical information, since equipment and methods are often closely associated.

Upon inquiring into this subject, the writer has found that the main objection to the Uren system on the part of librarians is that it cannot be fitted into any of the classifications now in use in the libraries. It was therefore decided to investigate the existing classification systems with a view of finding a division or group suitable for geophysical exploration, and then to subdivide this division in such manner that a consistent and self-contained classification would result.

The Dewey Classification System

A decimal classification system now in widespread use is the one devised by Dewey.[3] In this system, the entire field of knowledge is conceived as a unit and subdivided into the ten main classes shown in Table 1.

[2] Lester C. Uren: Decimal system for classifying data pertaining to the petroleum industry. *The Petroleum Engineer*, Dallas, Texas, 2nd ed. (undated), probably 1940.

[3] Melvil Dewey: *Decimal Classification and Relative Index*, 13th ed., 1932.

Class 5, Pure Science, is divided again into the divisions of Mathematics, Astronomy, Physics, Chemistry, and so forth, as shown in Table 2:

TABLE 1

Classes in the Dewey Decimal System

0	General Works
1	Philosophy
2	Religion
3	Social Sciences
4	Philology
5	Pure Science
6	Useful Arts; Applied Science
7	Fine Arts
8	Literature
9	History

TABLE 2

Science Divisions in the Dewey Decimal System

500	*Pure Science*
510	Mathematics
520	Astronomy
530	Physics
540	Chemistry
550	Geology
560	Paleontology
570	Biology. Anthropology
580	Botany
590	Zoology

From the viewpoint of Geophysical Exploration, the subdivisions of Physics (530) and Geology (550) are of special interest and are reproduced in Table 3:

TABLE 3

Subdivisions of the Physics and Geology Sections in the Dewey System

530	*Physics*	*550*	*Geology*
531	Mechanics	551	Physical and Dynamic Geology
532	Liquids. Hydraulics	552	Lithology. Petrography
533	Gases. Pneumatics	553	Economic Geology
534	Sound. Acoustics	554	Europe
535	Radiation. Light. Optics	555	Asia
536	Heat	556	Africa
537	Electricity	557	North America
538	Magnetism	558	South America
539	Molecular Physics	559	Oceanic, Polar Regions

Likewise of interest is the Applied Science division shown in Table 4, which is divided into Medicine, Engineering, Agriculture, and so forth.

The Engineering section, in turn, is divided into Mechanical, Mining, Military, etc. Engineering, as shown in Table 5:

TABLE 4

Applied Science Divisions

600	*Useful Arts, Applied Science*
610	Medicine
620	Engineering
630	Agriculture
640	Home Economics
650	Communication
660	Chemical Technology
670	Manufactures
680	Mechanic Trades
690	Building

TABLE 5

Subdivisions of the Engineering Section

620	*Engineering*
621	Mechanical
622	Mining
623	Military, Naval
624	Bridge and Roof
625	Road and Railroad
626	Canal
627	River and Harbor
628	Sanitary, Waterworks
629	Other branches

A detailed examination was made of the Dewey System in an attempt to find a suitable place for the subject of Geophysical Exploration. In the course of this examination, geophysical subjects were found to be widely scattered in the divisions of Astronomy, Physics, Chemistry, Geology, and Enginnering. Table 6 is a partial list of the subjects located in the edition available to the writer:

TABLE 6

Geophysical Subjects in the Astronomy, Physics, Chemistry, Geology, and Engineering Divisions of the Dewey Decimal System

520 Astronomy

525. Earth
.1 Constants
526. Geodesy
.1 Earth's Figure
.7 Gravity Measurements
Gravimeter
Torsion Balance

530 Physics

531. Mechanics
.5 Gravity
534. Sound. Acoustics
.6 Seismograph
.8 Applications
537. Electricity
.7 Measurements
.8 Applications
538. Magnetism
.7 Terrestrial Magnetism
.9 Applied Magnetism
539. Molecular Physics
.3 Elasticity
.7 Radioactivity

540 Chemistry

542. Practical Chemistry
.7 Gas Manipulation

550 Geology

551. Physical & Dynamic Geology (including Geophysics and Geochemistry)
.1 Structure of Earth
.2 Seismology

620 Engineering

622. Mining Engineering
.1 Exploration and Prospecting
.11 Theory, Applied Geology
.12 Prospecting, Practical Methods
.15 Magnetic Surveys

As far as Geophysical Exploration is concerned, there is seen to occur a certain amount of duplication which will result in filing difficulties. For instance, gravity measurements are listed under the heading of Geodesy but could also be filed in the Physics division, under the heading of Mechanics. In division 534, we find a listing for seismographs and applications of acoustics, and another subdivision of seismology is listed under the heading of physical and dynamic geology. Finally, the topic of elasticity appears under the heading of molecular physics (539). Magnetic surveys are scheduled as a subdivision of Mining Engineering while they might be listed with equal justification under 538.9 (Applied Magnetism). As proof of the confusion, one has but to walk into a number of libraries using the Dewey System and to inquire where Geophysical Exploration Methods are scheduled. It will be found that articles dealing with specific subjects are either distributed among the various branches of physics, or are listed collec-

tively under the heading of Geophysical Prospecting. Gravity surveys may appear in the Geodesy or in the Prospecting section, magnetic surveys may appear under Magnetism or under Mining Engineering, and so forth. As far as the subject of Geophysical Exploration as such is concerned, there is no agreement as to where it belongs. Some libraries carry it under 550 (General Geology), others under 551 (Physical and Dynamic Geology), and still others under 622.1 (Mining Engineering).

Several good reasons may be cited both for and against scheduling Geophysical Exploration under any of the three headings of Physics, Geology, and Engineering. The first two categories, according to the Dewey definition, are in the realm of Pure Science, and Geophysical Exploration is anything but Pure Science.[4] Most logically, our subject belongs in the Engineering class. However, it does not belong in Mining Engineering, where it is now listed in the Dewey Classification, since at present, at least, its industrial scope in oil prospecting outweighs that in Mining. A good place for it would be group 629 (Miscellaneous Branches of Engineering), but the question is whether physicists, geologists, or engineers, for that matter, would look for Geophysical Exploration in that category.

As far as the choice between Physics and Geology is concerned, this question places us right into the midst of the much debated issue whether Geophysical Prospecting should be regarded primarily as a physical or as a geological subject. The physicist will assure you that in Geophysical Exploration we are dealing exclusively with physical methods and procedures, and that the geological aspects are purely secondary. The geologist will contend with equal fervor that Geophysics is nothing but a tool of geology. In connection with our classification problem, however, we need not be too much concerned over this issue for various reasons. The first is that scheduling Geophysical Exploration in Physics would mean breaking up this subject into at least six groups, all listed under different numbers, with consequent loss of uniformity and continuity. The second reason is that such classification would not take care of the geological aspects of Geophysical Exploration, and would force us to make room for a parallel classification under the heading of Geology. This solution is exemplified by

[4] It should be noted that this discussion deals exclusively with Geophysical Exploration, or Geophysical Prospecting, and not with Geophysical Science, or Earth's Science.

the Harradon Classification[5] of magnetic literature in which magnetic instruments and measurements are classed under 538.7, whereas the descriptive and interpretative part is scheduled under 550.38. The third and main reason is that this controversy has, to all intents and purposes, been taken off our hands by the precedent of the Classification Décimale Universelle, discussed in the following section.

Classification Décimale Universelle

This classification system[6] may be considered an expansion of the Dewey decimal system. The significant divisions and numbers of the Dewey system have been retained and extended in this system. It has been used largely in Europe, but recently an English translation has become available, and it is understood that a number of libraries in this country have adopted it.

The Classification Décimale Universelle (C.D.U.) lists Geophysical Exploration under the general heading of "Applied and Practical Geology, and Prospecting" (550.8). The subdivisions, as given in the original French edition and in the revised English edition, are reproduced in Table 7.

It is believed that the position of Geophysical Exploration under 550.8 is probably the best that can be found under the circumstances, and that it is advantageous to leave it there since in this manner the least confusion will arise with the Dewey system.[7]

However, certain modificatic s of the 550.8 group appear to be in order. These are largely occasioned by the ever-expanding scope of the subject of Geophysical Exploration. At present, the C.D.U. places Geophysical Exploration on an equal footing with the so-called "primitive" methods of geological mapping, with the mechanical methods such as drilling and core analysis, with geochemical methods, with paleontological methods, with the divining rod, and with small-scale model experiments. The small-scale model experiments actually do not

[5] H. D. Harradon, Trans. of the Washington Meeting of the International Assoc. of Terr. Magnetism and Electricity, Sept. 4–15, 1939 (Bull. #11) (pp. 267–269, Edinburgh, 1940).

[6] Classification Décimale Universelle, Institut International de Bibliographie, Palais Mondial, Bruxelles, 4 volumes, 1927–1929.

[7] The 1932 edition of the Dewey Classification lists "Collective Works on General Geology" under 550.8. Following the consistent usage of the 0 digit elsewhere in the Dewey system, collective works should preferably be scheduled under 550.0 which would leave 550.8 available for Geophysical Exploration.

TABLE 7

Geophysical Exploration in the "Classification Décimale Universelle"

1927–29 ed. (4 volumes)	*Revised English Edition*
550.8 Recherches et prospections géologiques	550.800. *Applied & Practical Geology, Geological Research & Prospecting. Evaluation of Results. Experimental Studies.*
Études expérimentales	
.81 Méthodes primitives	10. *Primitive Methods*
.82 Méthodes mecaniques	20. *Mechanical Methods*
.83 Méthodes géophysiques	22. Drilling. Coring
.831 Méthodes gravimétriques	23. Measurements of fissures
.834 Méthodes sismiques et acoustiques	24. Examination of boulders
.835 Méthodes radiométriques	30. *Geophysical Methods*
.837 Méthodes électriques	31. Gravimetric methods
.838 Méthodes magnétiques	34. Seismic and acoustic methods
.839 Autres méthodes de prospection géophysique	.3 Refraction methods
.87 Méthodes biologiques et psychiques (Wünschelrute, Baguette divinatoire)	.4 Reflection methods
.89 Reproduction de phénomènes géologiques à pétite échelle. Géologie expérimentale.	35. Radiometric methods
	36. Geothermal methods
	37. Electrical methods
	.2 Surface potential methods
	.3 Resistivity methods
	.4 Electrical coring
	.6 Electromagnetic methods. Inductive methods other than wireless
	.7 Wireless methods
	38. Magnetic methods
	39. Other methods of geophysical prospect
	40. *Chemical and Physico-chemical Methods. Geochemical Methods*
	43. Electrochemical methods
	48. Gas Analysis methods
	60. *Paleontological Methods*
	61. Macroforaminifera
	62. Microforaminifera
	70. *Biological and Psychical Methods. Divining Rod*
	90. *Reproduction of Geologic Phenomena on Small Scale. Experimental Geology.*

belong under the heading of prospecting; in the interest of uniformity, another place should be found for this topic elsewhere under the heading of geology. The same is true of Micropaleontology, which much more logically should go in with Paleontology. Relative to the divining rod, the writer objects most strenuously to having Geophysical Exploration placed on an equal footing with what is generally conceded

to be an unscientific and at best psychological method. It is not clear what is meant by primitive methods; as far as mechanical methods (coring and drilling) are concerned, there is not much doubt that a more logical place can be found for them under other headings of purely geological character.

It may seem somewhat arbitrary to monopolize the entire 550.8 group for Geophysical Exploration. However, the present and expected future scope of our subject, compared with the other topics listed alongside with Geophysical Exploration in 550.8, leaves us hardly any other alternative. There is this advantage to the use of the entire group 550.8 for Geophysical Exploration: The decades following the 8 can be assigned to the various exploration methods, and the units can be used for the recurrent groups of general aspects, history, rock properties, instruments, corrections, interpretation, and so forth, which would place a second decimal point after the units as it should be. This, in substance, is the basis of the proposed classification system.

Proposed Classification System for Geophysical Exploration

In the proposed classification system, the subject of Geophysical Exploration is subdivided into ten groups, each of which are designated by successive decades as illustrated in Table 8:

TABLE 8

Principal Divisions of Classification

550.800.	*Geophysical Exploration*
.800.	General Aspects of Geophysical Exploration.
.810.	Gravimetric Methods.
.820.	Magnetic Methods.
.830.	Seismic, Acoustic and Related Methods.
.840.	Electrical Prospecting Methods.
.850.	Radioactivity Methods.
.860.	Geothermal Methods.
.870.	Geochemical Methods.
.880.	Geophysical Well Testing.
.890.	Miscellaneous Geophysical Methods.

In conformity with the usage of digits in the Dewey system, the digit 0 has been reserved for general topics. Gravimetric and Magnetic methods have been listed in succession because of their similarity of principle. This is followed by the Seismic and Electrical methods, after which are scheduled the Radioactivity, Geothermal, and Geochemical methods. In the eighth group are combined all Geophysical Well Testing methods. Group 9 is kept open for miscellaneous geophysical methods and is reserved for future use, in conformity with the usage of the digit 9 in the Dewey system.

Each of the main divisions, in turn, is subdivided into 10 recurrent groups listed in Table 9:

TABLE 9

Scheme of Subdivisions (Unit Digits)

00. General Topics, General Articles, Fundamentals.
01. History.
02. Physical Rock Properties.
03. Instruments and Procedures.
04. Corrections and Disturbing Effects.
05. Interpretation Theory.
06. Results.
07. Statistics.
08. Costs.
09. (Open).

Each of these groups has a significant digit in the unit position before the decimal point. This feature of the classification makes it possible always to identify a certain phase of any geophysical method without having to memorize lengthy figures, once the user has become familiar with the significance of the unit digits. Following the precedent of the Dewey system, the digit 0 always stands for general topics, reviews, or discussion of fundamentals, regardless of geophysical method. Number 9 is left open for future needs or miscellaneous other topics that cannot be fitted into the scheme given in Table 9. In the Dewey system, the digit 1 is generally used for general questions and stands here for historical treatments.

There is one exception to this rule, namely the group 00, which is not concerned with any particular geophysical methods but merely with the various general aspects of the entire field of Geophysical Exploration. Nevertheless, these general topics have been classified in as close conformity to the general scheme as possible. In the general group, the digit 0 indicates General Works; 01 indicates General History of the entire field; 07, Statistics of the Entire Field; 08 General Costs; and 09, Miscellaneous Unclassified General Aspects of Geophysical Exploration. The subgroups mentioned above are therefore indicated by the same digits as used elsewhere. The exceptions are the subgroups 02, signifying Geophysical Organization; 03, General Procedure; 04, Geophysical Education; 05 (usually indicating Interpretation) stands here for Legal Phases; and 06 (indicating Results elsewhere in the classification) stands here for reviews of the geological possibilities and applications of geophysical methods in oil, mining, and engineering.

The following tables represent the ten major groups in the pro-

posed classification, subdivided, in most cases, into the smaller first decimal groups. In some instances a further subdivision has been made (or suggested) for the first decimal groups where the more advanced state of the art has made such division desirable. In the first decimal groups there are quite a few unoccupied places, and ample room has been provided for future needs. Naturally, the subdivision into first and even second-decimal units can be pushed as far as the needs of individual users may require.

Group 00: General Aspects of Geophysical Exploration

This group is shown in Table 10 and deals with various general aspects of the entire geophysical field, irrespective of method. In

TABLE 10

550.800. General Aspects of Geophysical Exploration

00. General Principles. Fundamentals. Reviews of the Entire Field.

.0 General Reviews. Texts.
.1 Significance and scope of geophysical exploration.
.2 Relation between geophysical exploration and geophysical science.
.3 Relation between geophysical exploration and geology.
.4
.5 Bibliographies (entire field).
.6
.7 Classification systems.
.8
.9

01. General History of the Entire Field of Geophysical Exploration.

.0 General history.
.1
.2 History of geophysical exploration in oil prospecting.
.3
.4 History of geophysical exploration in mining.
.5
.6 History of geophysical exploration in engineering.
.7 History of military and naval applications of geophysics.
.8
.9

02. Geophysical Organizations. Geophysical Laboratories.

.0 General.
.1
.2 Scientific organizations. Professional organizations.
.3
.4 Industrial organizations.
.5
.6 Geophysical laboratories.
.7
.8
.9

TABLE 10

550.800. *General Aspects of Geophysical Exploration* (continued)

03. *General Procedure. Transportation. Housing. Surveying.*

.0 General.
.1 General procedure of measurement.
.2 Land transportation.
.3 Water transportation.
.4 Aerial transportation.
.5 Housing of geophysical parties.
.6 General supplies for geophysical parties.
.7 Surveying for geophysical exploration.
.8
.9

04. *Geophysical Education. Publicity.*

.0 General.
.1
.2 Geophysical education in universities and technical schools.
.3 Company training courses.
.4 Publicity by dissemination of literature.
.5 Publicity by radio.
.6
.7 Geophysical exhibits.
.8
.9

05. *Legal Phases of Geophysical Exploration. Insurance.*

.0 General.
.1 Trespass laws.
.2 Regulations governing the use of public roads and waters.
.3 Permit forms.
.4 Regulations governing transportation and use of explosives.
.5 Patent laws.
.6 Employer liabilities.
.7 Labor laws.
.8 Insurance.
.9 Geophysical surveys and assessment work.

06. *Reviews of Applications of Geophysical Exploration in Various Fields.*

.0 General.
.1
.2 Geophysical exploration in oil prospecting.
.3
.4 Geophysical exploration in mining.
.5
.6 Geophysical exploration in engineering.
.7 Military applications of geophysics. Naval applications.
.8
.9

07. *Geophysical Statistics (entire field).*

.0 General.
.1
.2 Statistics on geophysical exploration in oil prospecting.
.3
.4 Statistics on geophysical exploration in mining.
.5
.6 Statistics on geophysical exploration in engineering.
.7 Statistics on military and naval uses of geophysics.
.8
.9

TABLE 10

550.800. *General Aspects of Geophysical Exploration* (continued)

08. *Cost of Geophysical Exploration (entire field).*
- .0 General.
- .1 General cost of field operations.
- .2 Transportation costs alone.
- .3 Housing costs alone.
- .4 Surveying costs alone.
- .5 Cost of laboratory operation and research.
- .6 Training cost.
- .7 Cost of publicity.
- .8 Cost of legal services. Patent costs.
- .9 Permit fees.

09. *Miscellaneous General Aspects of Geophysical Exploration.*
- .0
- .1
- .2
- .3
- .4
- .5
- .6
- .7
- .8
- .9

the subgroup 00, general reviews and texts covering Geophysical Exploration as a whole would be filed. This subgroup would also be the place for bibliographies and classifications, provided they cover the entire field. The next subgroup, 01, is concerned with the history of Geophysical Exploration (entire field); its subdivisions cover the three main applications of geophysical prospecting in oil, mining, and engineering. Subgroup 02 is set aside for Geophysical Organizations and Laboratories, while subgroup 03 covers general measurement procedure, transportation, housing, and surveying in geophysical parties. In the next group, we find combined the educational and publicity aspects of geophysical exploration. Subgroup 05 deals with various important legal phases; for instance, trespass laws, patent laws, labor laws, and regulations covering the use of highways, waterways, and explosives. The next two subgroups, 06 and 07, are similar in structure and cover the statistics and general geological possibilities of geophysical methods in oil, mining, and engineering. Subgroup 08 is concerned with general cost data on geophysical surveys; this topic is broken down into general costs of operations, and cost data for transportation, housing, laboratory work, legal services, publicity, patents, etc.

Group 10: Gravimetric Methods

This group is shown in Table 11. It is subdivided in accordance with the general scheme set forth in Table 9.

TABLE 11

550.810. Gravimetric Methods

10. General Reviews. Fundamentals.

.0 General reviews of gravimetric prospecting.
.1
.2 The earth's gravitational field.
.3
.4 Theorem of Clairaut.
.5
.6 Space geometry of equipotential surfaces of gravity.
.7
.8
.9

11. History of Gravimetric Prospecting.

.0 General history of gravimetric prospecting.
.1 Historical data on determinations of gravitational constant.
.2
.3 Historical data on pendulum apparatus and methods.
.4 Historical data on gravimeters.
.5 Historical data on the Eoetvoes torsion balance.
.6
.7 Historical data on measurements of time variations of gravity.
.8 Historical data on measurements of deflections of the vertical.
.9

12. Rock Densities and Related Properties. Methods of Density Determination.

.0 General. Definitions.
.1
.2 Methods for determining rock density.
.3 Methods for determining porosity.
.4
.5
.6
.7
.8 Factors affecting formation densities.
.9 Tabulations of densities.

13. Instruments, Methods, Field Procedures.

.0 General aspects of instrument and field operation.
.1 Methods and instruments for determining the gravitational constant.
.2 Gravity compensator. Gravity multiplicator.
.3 Pendulum apparatus and methods.
.4 Gravimeters.
.5 Eoetvoes torsion balance.
.6 Gravity gradiometers, horizontal and vertical.
.7 Instruments for recording time variations of gravity.
.8 Instruments and methods for measuring deflections of the vertical.
.9

14. Corrections in Gravimetric Prospecting.

.0 Instrument-corrections and calibration of pendulum apparatus.
.1 Instrument-corrections and calibration of gravimeters.
.2 Instrument-corrections and calibration of torsion balances.
.3 Free-Air correction.
.4 Bouguer correction.
.5 Terrain correction for gravity (vert. and hor. components).
.6 Terrain correction for gravity gradients (hor. vert., curvature values).
.7 Planetary corrections for gravity and gravity gradient.
.8 Regional correction for gravity and gravity gradient
.9

TABLE 11

550.810. *Gravimetric Methods* (continued)

15. *Interpretation of Gravity Anomalies.*
- .0 General relations. General procedure.
- .1 Analytical methods in gravity interpretation.
- .2 Analytical methods in torsion balance interpretation.
- .3
- .4 Graphical methods in gravity interpretation.
- .5 Graphical methods in torsion balance interpretation.
- .6
- .7 Mechanical integration methods in gravity interpretation.
- .8 Mechanical integration methods in torsion balance interpretation.
- .9

16. *Results of Gravimetric Exploration.*
- .0 General.
- .1
- .2 Regional gravity surveys by pendulums.
- .3 Surveys of geologic structures by pendulums.
- .4 Regional gravity surveys by gravimeters.
- .5 Surveys of geologic structures by gravimeters.
- .6 Regional gravity surveys by torsion balance.
- .7 Surveys of geologic structures by torsion balance.
- .8
- .9

17. *Statistics.*
- .0 General statistics on gravimetric exploration.
- .1
- .2
- .3 Statistics on pendulum surveys.
- .4 Statistics on gravimeter surveys.
- .5 Statistics on torsion balance surveys.
- .6
- .7
- .8
- .9

18. *Cost of Gravimetric Exploration.*
- .0 General cost data.
- .1
- .2
- .3 Cost of pendulum surveys.
- .4 Cost of gravimeter surveys.
- .5 Cost of torsion balance surveys.
- .6
- .7
- .8
- .9

19. *Time Variations of the Gravitational Field.*
- .0 General.
- .1
- .2 Lunar and solar variations.
- .3 Secular (isostatic) variations.
- .4
- .5
- .6 Water tides.
- .7
- .8 Subsurface mass displacements.
- .9

Subgroup 10 includes general reviews of the method and discussions of the Earth's gravitational field, of the theorem of Clairaut, and similar general subjects related to the measurement of gravity and gravity-gradient. In the first-decimal subdivisions, consistent use has been made of the digits 3, 4, and 5 to indicate pendulum, gravimeter, and torsion balance, respectively, in the subgroups 11, 13, 17, and 18. The subgroup on corrections takes into account instrument corrections, Bouguer correction, terrain correction, planetary, and regional corrections for gravity and gravity gradient. The subgroup on interpretation is divided into analytical, graphical, and mechanical integration methods. Results, in subgroup 16, are classified relative to regional surveys and surveys of more local significance. In subgroup 19, a separate section is devoted to time-variations of the gravitational field.

Group 20: Magnetic Methods

This group is tabulated in Table 12, and is subdivided in accordance with the general scheme set forth in Table 9.

TABLE 12

550.820. Magnetic Methods

20. General Reviews. Fundamentals.
- .0 General reviews.
- .1
- .2 The earth's magnetic field.
- .3
- .4
- .5
- .6
- .7
- .8
- .9

21. History of Magnetic Prospecting.
- .0 General history of magnetic prospecting.
- .1
- .2
- .3
- .4 History of magnetic prospecting in mining.
- .5
- .6 History of magnetic prospecting in oil exploration.
- .7
- .8 History of magnetic prospecting in civil and military engineering.
- .9

22. Magnetic Properties of Rocks.
- .0 General. Definitions.
- .1
- .2 Methods for determining rock magnetism.
- .3
- .4

TABLE 12

550.820. *Magnetic Methods* (continued)

.5
.6
.7
.8 Factors affecting rock magnetism.
.9 Tabulations of magnetic rock properties.

23. *Magnetic Instruments, Methods, and Field Procedure.*
.0 General construction principles. General field operation.
.1 General theory of magnetic instruments.
.2 Schmidt magnetometers.
.3 Superdip.
.4 Other prospecting magnetometers.
.5 Magnetic theodolite.
.6 Earth inductors for direction and intensity measurements.
.7 Miscellaneous magnetic instruments.
.8 Observatory and variation recording instruments.
.9

24. *Instrument Calibration, Corrections, Disturbing Effects.*
.0 General.
.1 General aspects of magnetometer calibration.
.2 Temperature and other instrument corrections.
.3 Diurnal and other variation corrections.
.4 Planetary correction.
.5 Base correction.
.6 Influence of iron and steel objects.
.7 Terrain effects.
.8 Normal field and regional anomalies.
.9

25. *Interpretation of Magnetic Anomalies.*
.0 General procedure.
.1 Graphical representation methods.
.2 Pole theory.
.3 Line theory.
.4 Induction theory for (uniformly) magnetized bodies.
.5 Magnetic anomalies in relation to gravitational anomalies.
.6 Interpretation theory based on both induced and permanent magnetization.
.7 Model experiments.
.8 Interpretation of observations in different levels.
.9

26. *Results of Magnetic Exploration.*
.0 General results.
.1
.2 Regional magnetic surveys.
.3
.4 Magnetic surveys of geologic structures and orebodies in mining.
.5
.6 Magnetic surveys of geologic structure in oil exploration.
.7
.8 Magnetic surveys in civil and military engineering.
.9

27. *Statistics.*
.0 General statistics on magnetic prospecting.
.1
.2
.3

TABLE 12

550.820. *Magnetic Methods* (continued)

.4 Statistics of magnetic exploration in mining.
.5
.6 Statistics of magnetic exploration in oil prospecting.
.7
.8 Statistics of magnetic exploration in civil and military engineering.
.9

28. *Cost of Magnetic Exploration.*
.0 General cost data.
.1
.2
.3
.4 Cost of magnetic exploration in mining.
.5
.6 Cost of magnetic exploration in oil prospecting.
.7
.8 Cost of magnetic exploration in civil and military engineering.
.9

29.
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.3
.4
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.7
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.9

The correction subgroup (24) provides for instrument corrections and calibration, diurnal-variation-correction, planetary correction, and effects of terrain and iron and steel objects. In the interpretation group (25) we find such topics as the pole-, the line-, and the induction-theories; interpretation based on both induced and permanent magnetization, model experiments, and observations in different levels. In the subgroup (26) on results, allowance is made for the three principal applications of magnetic prospecting in mining, oil prospecting, and engineering. The same numbering system in the decimals is carried through into the groups on Statistics and Costs (27 and 28).

Group 30: Seismic, Acoustic, and Related Methods

This group, shown in Table 13, may appear rather crowded due to the fact that two or more geophysical methods which are of rather unequal significance at present have been placed together. This was done advisedly in view of possible future developments along the line of methods on the borderline of acoustic and seismic procedures. For the same reason, the various seismic techniques have been subordinated, as first-decimal items, to the general scheme of Table 9

TABLE 13

550.830. Seismic, Acoustic, and Related Methods

30. General Reviews, Fundamentals.
- .0 Reviews of seismic, acoustic and related methods (entire field).
- .1 Relation of seismic exploration to earthquake seismology.
- .2 General treatments of seismic wave propagation.
- .3 General reviews of fan and arc shooting methods.
- .4 General reviews of seismic refraction methods.
- .5 General reviews of seismic reflection methods.
- .6 General reviews of engineering seismology.
- .62 Gen. rev. of eng. seismology: Rock burst investigations.
- .64 Gen. rev. of eng. seismology: Free-vibration test methods.
- .66 Gen. rev. of eng. seismology: Forced vibration (dynamic) test methods.
- .68 Gen. rev. of eng. seismology: Strain-gauging methods.
- .7 General reviews of acoustic methods.
- .72 General reviews of acoustic methods: atmospheric-acoustic methods.
- .74 General reviews of acoustic methods: marine-acoustic methods.
- .76 General reviews of acoustic methods: geoacoustic methods.
- .8
- .9

31. History of Seismic, Acoustic, and Related Methods.
- .0 Decimal divisions same as in #30.

32. Elastic Rock Properties, Seismic Wave Velocities, Acoustic Resistivity, etc.
- .0 General. Definitions. Units.
- .1 Elastic moduli.
- .2 Laboratory methods for measuring elastic moduli.
- .3 Types and velocities of seismic and acoustic waves.
- .4 Field methods for measuring seismic wave speeds.
- .5 Acoustic resistivity and related properties.
- .6 Absorption. Scattering. Dispersion.
- .7 Damping resistance. Methods for determining damping resistance.
- .8 Factors affecting elastic rock properties.
- .9 Tabulations of elastic rock properties.

33. Seismic (receiving) Instruments. Seismic and Acoustic Procedures.
(Seismic and Acoustic transmitters are scheduled in #39.)
- .0 General. Classification. General Theory.
- .1 Theory and construction of seismic and acoustic detectors.
- .2 Shot instant transmission, timing, communication, photographic recording.
- .3 Procedure in fan arc shooting.
- .4 Procedure in refraction shooting.
- .5 Procedure in reflection shooting.
- .6 Procedure in engineering seismology. (See #30 for divisions)
- .7 Procedure in acoustic detection. (See #30 for divisions)
- .8
- .9

34. Instrument-Calibration. Corrections. Disturbing Effects.
- .0 General.
- .1 Instrument calibration.
- .2 Instrument corrections.
- .3 Corrections in fan and arc shooting.
- .4 Corrections in refraction shooting.
- .5 Corrections in reflection shooting.
- .6 Corrections and disturbing effects in engineering seismology. (See #30 for divisions)
- .7 Corrections and disturbing effects in acoustic detection. (See #30 for divisions)
- .8
- .9

TABLE 13

550.830. *Seismic, Acoustic, and Related Methods* (continued)

35. *Theory of Wave Propagation. Interpretation Methods.*
- .0 General Reviews.
- .1
- .2
- .3 Interpretation of fan and arc shooting results.
- .4 Interpretation of refraction results.
- .5 Interpretation of reflection results.
- .6 Interpretation of results in engineering seismology (dec. div., see #30)
- .7 Interpretation of results in acoustic methods (dec. div., see #30)
- .8
- .9

36. *Results of Seismic, Acoustic, and Related Methods.*
- .0 General reviews.
- .1
- .2
- .3 Results of fan and arc shooting.
- .4 Results of refraction shooting.
- .5 Results of reflection shooting.
- .6 Results in engineering seismology (dec. div., see #30).
- .7 Results of acoustic methods (dec. div., see #30).
- .8
- .9

37. *Statistics on Seismic, Acoustic, and Related Methods.*
- .0 General statistics on all seismic and acoustic methods.
- .1
- .3
- .3 Statistics on fan and arc shooting.
- .4 Statistics on refraction shooting.
- .5 Statistics on reflection shooting.
- .6 Statistics on engineering seismology (dec. div., see #30).
- .7 Statistics on acoustic methods (dec. div., see #30).
- .8
- .9

38. *Costs of Seismic, Acoustic, and Related Methods.*
- .0 General data on cost of seismic methods.
- .1
- .2
- .3 Cost of fan and arc shooting.
- .4 Cost of refraction shooting.
- .5 Cost of reflection shooting.
- .6 Cost of tests in engineering seismology (dec. div., see #30).
- .7 Cost of acoustic detection (dec. div., see #30).
- .8
- .9

39. *Generation of Seismic and Acoustic Energy.*
- .0 General.
- .1 Mechanical, impulse and low frequency transmitters (shakers, etc.).
- .2 Acoustic transmitters.
- .3 Drilling equipment for shot holes.
- .4
- .5 Shooting technique.
- .6 Explosives.
- .7 Portable powder magazines.
- .8
- .9

frequently referred to. At the same time, a consistent arrangement of first-decimal topics has been used wherever possible. In all subgroups with the exception of 32 and 39, the first-decimal digit 3 stands for fan and arc shooting, 4 for refraction, 5 for reflection, 6 for engineering-seismology, and 7 for acoustic methods. It is felt that if future developments make a revision of these categories desirable, it will be easier to do that in the first decimal items than in the unit groups for which it was desired to retain a uniform significance. In subgroup 30, the topics of Engineering Seismology and Acoustic Methods have been broken down further to indicate the procedure to be used in the other following subgroups.

Considerable room has been given to physical rock properties; not only to those which are now recognized as being of prime importance in seismic and acoustic work, but also to others than may become more important in the future, such as acoustic resistivity, absorption, dispersion, and damping resistance. In the group on instruments, it will be noted that theory of seismic and acoustic detectors has been combined. Seismic and acoustic transmitters are included, together with other means of generating seismic energy, in a separate subgroup at the end of the seismic section. In subgroup 34, instrument-corrections and calibration have been scheduled together with other corrections required in fan-, refraction-, and reflection-shooting. This procedure may be open to dispute since instrument correction and calibration may also be classed in subgroup 33 (seismic and acoustic instruments). A last group, 39, has been set aside, as mentioned before, for topics related to the generation of seismic and acoustic energy, and includes shot-hole drilling and explosives.

Group 40: Electrical Prospecting Methods

The arrangement of this group, shown in Table 14, is similar in many ways to that of the preceding seismic group.

TABLE 14

550.840. Electrical Prospecting Methods

40. General Reviews. Fundamentals.

.0 General reviews of electrical methods (entire field).
.1 Reviews and fundamentals of self-potential method.
.2 Reviews and fundamentals of equipotential line and potential profile method. DC and AC fields. Elliptical polarization of potential field. Depth penetration.
.3 Reviews and fundamentals of resistivity methods.
.4 Reviews and fundamentals of potential-drop-ratio method.
.5 Reviews and fundamentals of other potential methods (Eltran, etc.)
.6 Reviews and fundamentals of electromagnetic galvanic methods.

TABLE 14

550.840. *Electrical Prospecting Methods* (continued)

.7 Reviews and fundamentals of electromagnetic-inductive methods. Elliptical polarization of electromagnetic field. Depth penetration.
.8 Reviews and fundamentals of radio methods. Treasure and pipe finders. Propagation of radio waves.
.9

41. *History of Electrical Prospecting.*
Same divisions as in 40.

42. *Electrical Rock Properties.*
.0 General. Definitions. Units.
.1 Rock resistivity.
.2 Laboratory and field methods for measuring rock resistivity.
.3 Electrochemical properties.
.4 Methods for measuring electrochemical properties.
.5 Dielectric properties.
.6 Methods for measuring dielectric properties.
.7
.8 Factors affecting electrical rock properties.
.9 Tabulations of electrical rock properties.

43. *Electrical Prospecting Instruments, Methods and Field Procedures.*
.0 General. Electrodes, generators, receivers, amplifiers.
.1 Self-potential method. Corrosion surveys.
.2 Equipotential-line and potential-profile methods. Potential compensators.
.3 Resistivity methods. Electrode arrangements. Instruments. Procedures.
.4 Potential-drop-ratio method. Potential ratiometers.
.5 Other potential methods (Eltran, etc.)
.6 Electromagnetic-galvanic methods. Field compensators, ratiometers.
.7 Electromagnetic-inductive methods. Bieler-Watson, Sundberg method.
.8 Radio methods. Treasure and pipe finders.
.9

44. *Corrections and Disturbing Effects in Electrical Prospecting.*
.0 General.
The following groups may be subdivided in the 2d decimal into the following topics: effects of terrain, surface features, power leads and loops, normal field. etc.
.1 Self-potential and corrosion surveys.
.2 Equipotential-line and potential-profile methods.
.3 Resistivity methods.
.4 Potential-drop-ratio methods.
.5 Other potential methods (Eltran, etc.)
.6 Electromagnetic-galvanic methods.
.7 Electromagnetic-inductive methods.
.8 Radio methods. Treasure and pipe finders.
.9

45. *Theory and Procedure of Interpretation in Electrical Prospecting.*
.0 General Principles.
.1 Interpret. theory, practice, and model exp. in self-potential methods.
.2 Interpret. theory, practice, and model exp. in equipotential-line, and potential-profile methods.
.3 Interpret. theory, practice, and model exp. in resistivity methods.
.4 Interpret. theory, practice, and model exp. in pot.-drop-ratio methods.
.5 Interpret. theory, practice, and model exp. in other potential methods.

TABLE 14

550.840. Electrical Prospecting Methods (continued)

.6 Interpret. theory, practice, and model exp. in electromag-galv. methods.
.7 Interpret. theory, practice, and model exp. in electromag.-ind. methods.
.8
.9

46. Results of Electrical Surveys.

.0 General results in oil exploration, mining, civil, and military eng.
.1 Results of self-potential and corrosion surveys.
.2 Results of equipot.-line surveys and potential profiles.
.3 Results of resistivity surveys in mining, oil exploration and eng.
.4 Results of potential-drop-ratio surveys.
.5 Results of other potential surveys (Eltran, etc.)
.6 Results of electromagnetic-galvanic surveys.
.7 Results of electromagnetic-inductive surveys.
.8 Results of radio surveys and work with treasure and pipe finders.
.9

47. Statistics on Electrical Prospecting.

.0 General statistics on (all) electrical prospecting methods.
.1 Statistics on self-potential and corrosion surveys.
.2 Statistics on equipotential-line and potential-profile surveys.
.3 Statistics on resistivity surveys.
.4 Statistics on potential-drop-ratio surveys.
.5 Statistics on other potential (Eltran, etc.) surveys.
.6 Statistics on electromagnetic-galvanic surveys.
.7 Statistics on electromagnetic-inductive surveys.
.8 Statistics on radio surveys and work with treasure and pipe finders.
.9

48. Cost of Electrical Prospecting.

.0 General cost data on electrical prospecting (entire field).
.1 Cost of self-potential surveys.
.2 Cost of equipotential-line and potential-profile surveys.
.3 Cost of resistivity surveys.
.4 Cost of potential-drop-ratio surveys.
.5 Cost of other potential (Eltran, etc.) surveys.
.6 Cost of electromagnetic-galvanic surveys.
.7 Cost of electromagnetic-inductive surveys.
.8 Cost of radio surveys and of treasure and pipe finder surveys.
.9

49.

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Again, the various electrical methods are subordinated as first-decimal items to the general scheme listed in Table 9, thus allowing an easier changeover if called for by future development. In all subgroups of the electrical prospecting group with the exception of 42, a consistent

numbering system is applied to indicate the method. Thus, .1 indicates the self-potential method; .2 the equipotential-line method; .3 resistivity, and so forth. In this manner, any topic in electrical prospecting may be readily located in the classification. In subgroup 42, the principal items listed are rock resistivity, electrochemical and dielectric properties, and methods for measuring them. The entire subgroup 49 is left open for future needs.

Group 50: Prospecting by Radioactivity

For this group, tabulated in Table 15, only the main subgroups are listed from 51 to 52 and from 54 to 59.

TABLE 15

550.850. *Prospecting by Radioactivity (exclusive of Radioac. Well-Logging)*

50. *General Reviews. Fundamentals.*

51. *History of Prospecting by Radioactivity.*

52. *Radioactivity of Rocks.*

53. *Instruments, Methods, & Field Procedure in Prospecting by Radioactivity.*

.2 Measurements of total and alpha radiation of soil samples.
.3 Measurements of gamma radiation of soil samples (Geiger counter).
.5 Measurements of Radon/Helium ratio on soil samples.
.7 Measurements of total or alpha radiation with ionization chambers.
.8 Measurements of gamma radiation with ionization chambers.

54. *Corrections & Disturbing Influences in Radioactivity Prospecting.*

55. *Interpretation of Radioactivity Measurements.*

56. *Results of Prospecting by Radioactivity.*

57. *Statistics on Prospecting by Radioactivity.*

58. *Cost of Prospecting by Radioactivity.*

59.

In 53, a division of methods and procedures has been indicated; should the need arise, these divisions can be carried over into the other subgroups. It should be noted that this group (radioactivity prospecting) deals only with surface prospecting and does not include gamma-ray and other radioactivity well-logging.

Group 60: Geothermal Prospecting

This group likewise includes only the techniques of surface prospecting by temperature measurements in shallow holes, and not the techniques of temperature-logging in deep wells. In Table 16, only the main subgroups are indicated, since no further subdivision seems to be required at this time.

TABLE 16

550.860. *Geothermal Prospecting (exclusive of Geothermal Well-Logging)*

60. *General Reviews and Fundamentals.*
61. *History of Geothermal Prospecting.*
62. *Thermal Rock Properties.*
63. *Geothermal Instruments and Methods.*
64. *Corrections and Disturbing Influences in Geothermal Prospecting.*
65. *Interpretation of Geothermal Prospecting Results.*
66. *Results of Geothermal Prospecting.*
67. *Statistics on Geothermal Prospecting.*
68. *Cost of Geothermal Prospecting.*
69.

Group 70: Chemical, Physico-Chemical, and Biological Exploration Methods

These methods are still in the state of development and definite subdivisions are not too readily established. Therefore, Table 17 contains, in the main, a listing of the customary subgroups, and only in subgroup 73 a tentative scheme of subdivisions has been indicated. This can be modified if necessary and be carried over into the other subgroups.

TABLE 17

550.870. *Chemical, Physico-Chemical, and Biological Exploration Methods*

70. *General Reviews of Chemical Exploration Methods.*
71. *History of Chemical Exploration Methods.*
72. *Chemical Properties of Near-Surface Soils, Waters, Gases, and Plants.*
73. *Procedures and Instruments in Chemical and Physico-Chemical Methods.*
  .0 General Procedure. Technique of sample collection.
  .1 [redacted]
  .2 Hydrocarbon gas-detection methods.
  .3 Hydrocarbon soil-analysis methods.
  .4 Hydrocarbon soil-wax extraction methods.
  .5 Geochemical water-analysis methods.
  .6 Soil-Analysis for metals etc.
  .7 Plant-Analysis for metals, etc.
  .8 Other biological exploration methods.
  .9
74. *Disturbing Influences and Corrections in Geochemical Exploration.*
75. *Interpretation of Geochemical Results.*
76. *Results of Geochemical Exploration.*
77. *Statistics on Geochemical Exploration.*
78. *Cost of Geochemical Exploration.*
79.

Group 80: Geophysical Well-Testing Methods

The ever increasing application of geophysical methods to production problems accounts for the fact that the first-decimal items, indicating the various well-testing methods, are taken up completely, with the customary exception of the 0.9 division. The various well-testing methods are subordinated to the general scheme of Table 9 and include, in consistent numbering throughout all subgroups (except 82 and 89): Electrical Well-Logging, Geothermal Well-Logging, Well-Logging by Radioactivity, Photoelectric Well-Logging, Geochemical and Magnetic Core Analysis, Seismic and Acoustic Measurements, and Mud Logging. In subgroup 82, this numbering system does not apply; various physical properties of formations, of drilling fluids, of cement, oil and water, significant in the art of geophysical well-logging, are listed here. Subgroup 89 has been set aside for techniques of depth measurement in various methods of geophysical well-logging.

TABLE 18

550.880. Geophysical Well-Testing Methods

80. General Reviews and Fundamentals.

.0 General reviews of well-testing methods (entire field).
.1 Reviews of electrical well-logging methods.
.2 Reviews of geothermal well-logging methods.
.3 Reviews of well-logging by radioactivity.
.4 Reviews of photoelectric well-logging methods.
.5 Reviews of geochemical core analysis methods.
.6 Reviews of magnetic core analysis methods.
.7 Reviews of seismic and acoustic well-testing methods.
.8 Reviews of mud logging methods.
.9

81. History of Geophysical Well-Testing.

.0 History of geophysical well-testing (entire field).
.1 History of electrical well-logging.
.2 History of geothermal well-logging.
.3 History of well logging by radioactivity.
.4 History of photoelectric well-logging.
.5 History of geochemical core analysis.
.6 History of magnetic core analysis.
.7 History of seismic and acoustic well-testing.
.8 History of mud logging.
.9

82. Physical Properties in Geophysical Well-Testing.

.0 General data on physical properties.
.1 Resistivities and electrochemical properties of rocks, drilling fluids, oil, and water.
.2 Thermal properties of formations, drilling fluids, oil, water, cement.
.3 Radioactivity of formations, water, oil, cements, etc.
.4 Optical properties of drilling fluids, water, oil, etc.
.5 Chemical properties of formations, drilling fluids, water, oil, etc.

TABLE 18

550.880. *Geophysical Well-Testing Methods* (continued)

.6 Magnetic properties and polarity of drill cores.
.7 Seismic and acoustic prop. of formations, drilling fluids, oil, water, etc.
.8 Physical properties of muds involved in mud logging.
.9

83. Geophysical Well-Testing Instruments and Procedures.

.0 General principles of geophysical well-testing instruments; procedures.
.1 Apparatus and procedure in electrical well-logging.
.2 Apparatus and procedure in geothermal well-logging.
.3 Apparatus and procedure in well-logging by radioactivity.
.4 Apparatus and procedure in photoelectric well-logging.
.5 Apparatus and procedure in geochemical core analysis.
.6 Apparatus and procedure in magnetic core analysis.
.7 Apparatus and procedure in seismic and acoustic well-testing.
.8 Apparatus and procedure in mud logging.
.9

84. Corrections and Disturbing Influences in Geophysical Well-Testing.

.0 General.
.1 Disturbing effects and corrections in electrical well-logging.
.2 Disturbing effects and corrections in geothermal well-logging.
.3 Disturbing effects and corrections in well-logging by radioactivity.
.4 Disturbing effects and corrections in photoelectric well-logging.
.5 Disturbing effects and corrections in geochemical core analysis.
.6 Disturbing effects and corrections in magnetic core analysis.
.7 Disturbing effects and corrections in seismic and acoustic well-logging.
.8 Disturbing effects and corrections in mud logging.
.9

85. Interpretation of Geophysical Well Data.

.0 General procedure of interpretation.
.1 Interpretation of electrical well logs.
.2 Interpretation of geothermal well logs.
.3 Interpretation of radioactivity well logs.
.4 Interpretation of photoelectric well logs.
.5 Interpretation of geochemical core analyses.
.6 Interpretation of magnetic core analyses.
.7 Interpretation of seismic and acoustic well-testing data.
.8 Interpretation of mud logs.
.9

86. Results of Geophysical Well-Testing.

.0 General results.
.1 Results of electrical well-logging.
.2 Results of geothermal well-logging.
.3 Results of well-logging by radioactivity.
.4 Results of photoelectric well-logging.
.5 Results of geochemical core analysis.
.6 Results of magnetic core analysis.
.7 Results of seismic and acoustic well-testing.
.8 Results of mud logging.
.9

87. Statistics on Geophysical Well-Logging.

.0 General statistics on geophysical well-testing.
.1 Statistics on electrical well-logging.
.2 Statistics on geothermal well-logging.
.3 Statistics on well-logging by radioactivity.

TABLE 18

550.880. Geophysical Well-Testing Methods (continued)

.4 Statistics on photoelectric well-logging.
.5 Statistics on geochemical core analysis.
.6 Statistics on magnetic core analysis.
.7 Statistics on seismic and acoustic well-testing.
.8 Statistics on mud logging.
.9

88. Cost of Geophysical Well-Testing.
.0 etc. Decimal Divisions same as in 87.

89. Depth Measurements in Geophysical Well-Testing.
.0 etc. Decimal Divisions same as in 87.

TABLE 19

550.890. Miscellaneous Geophysical Methods

Undivided at present.

Group 90: Miscellaneous Geophysical Methods

This group is undivided at present and any use of this heading is not believed to be required for some time to come, since most of the more important physical principles involved in the applications of geophysical methods are fairly well covered in the other groups. It is, of course, expedient to have a group set aside for future emergency.

Acknowledgments

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DETERMINATION OF THE BOUGUER CORRECTION CONSTANT*

A. J. F. SIEGERT†

ABSTRACT

A formula is given which eliminates some of the usual graphical work and makes the result independent of the judgment of the computer. The probable error can be determined easily.

In gravimetric surveying a correction for elevation differences is applied by adding to the measured values the quantity kh, where h is the elevation difference between the station and the reference horizon. k is a constant which depends on the density of the surface layer. The method which is usually employed to determine k empirically[1] involves much labor and relies on the personal judgment of the computer. In what follows an improved procedure is proposed. This procedure eliminates the personal factor and saves a great deal of work.

Gravity and elevation values of N stations on a straight line are plotted against the distance of the stations from an arbitrarily chosen starting point, as shown in the graph. In both profiles the points representing stations 1 and 3 are connected with straight lines. The gravity and the elevation represented by the straight line at station 2 are called respectively the interpolated value of gravity and elevation at station 2. The differences between the true values and the interpolated values are called g_2 and h_2 respectively. They are counted positive if the true value lies above the interpolated value. This procedure is repeated, connecting stations 2 and 4, 3 and 5, etc., in order to obtain g_3 and h_3, g_4 and h_4, etc. If the true gravity varied linearly with the distance, then, apart from observational errors, g_i and h_i would satisfy the equation

$$g_i = -kh_i$$

at each station. Actually true gravity is represented by a curved profile. The curvature of the latter, however, is much smaller than the curvatures of the uncorrected gravity profile. Furthermore, the interesting maxima and minima of gravity are not correlated with terrain anomalies. We therefore include the effects of the curvature of the true gravity profile in the observational errors and apply the Gaussian method of least squares, demanding that

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[1] L. L. Nettleton, GEOPHYSICS, IV, 176, 1939.

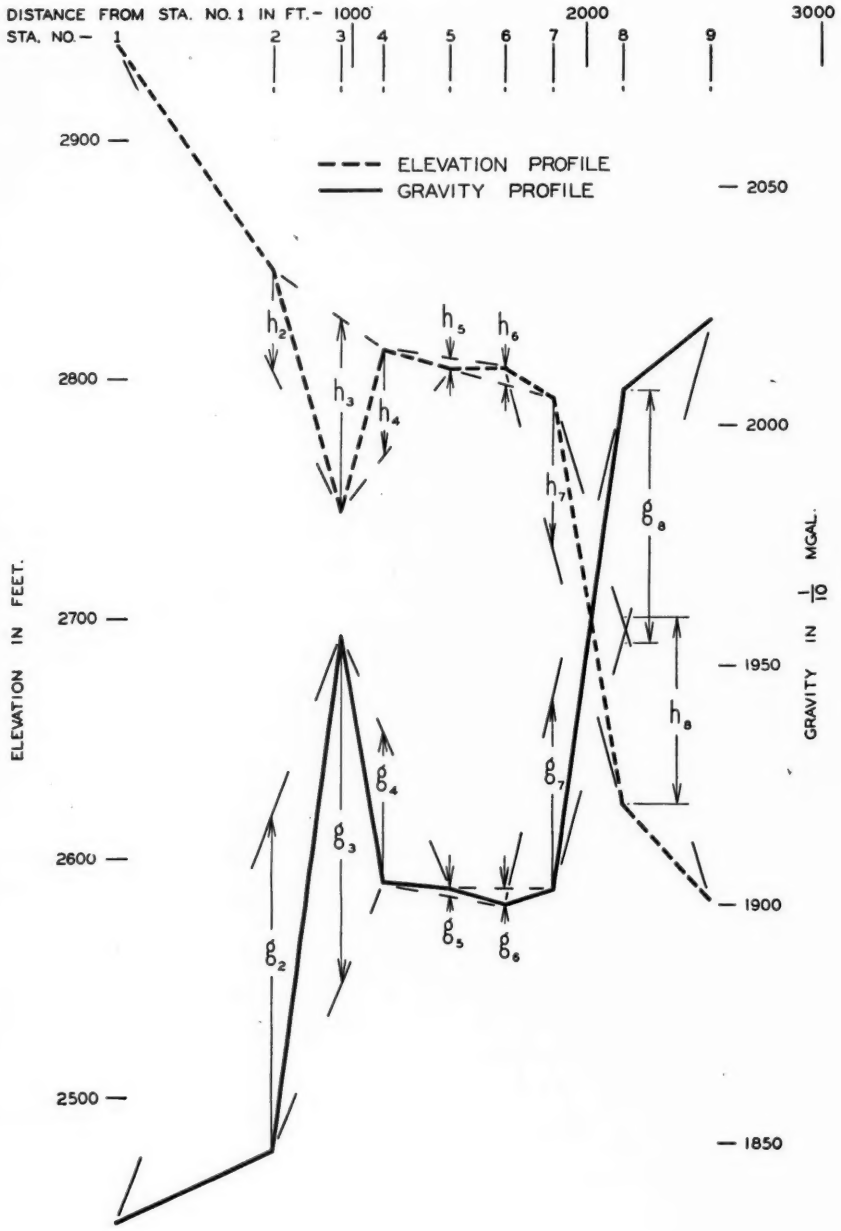
DISTANCE FROM STA. NO. 1 IN FT. – 1000
2000
3000
STA. NO. – 1
2
3
4
5
6
7
8
9
2900
2800
2700
2600
2500
ELEVATION IN FEET.
ELEVATION PROFILE
GRAVITY PROFILE
2050
2000
1950
1900
1850
GRAVITY IN 1/10 MGAL.
h2
h3
h4
h5
h6
h7
h8
g2
g3
g4
g5
g6
g7
g8

FIG. 1.

$$\sum_{i=2}^{N-1} (g_i + kh_i)^2$$

become a minimum.[2] This obviously is the mathematical formulation of the demand to choose k so as to make the corrected gravity profile as smooth as possible, because it minimizes the differences between the measured and interpolated values of the corrected gravity.

Standard mathematical procedure yields the value

$$k = -\frac{\sum_{i=2}^{N-1} h_i g_i}{\sum_{i=2}^{N-1} h_i^2} \tag{1}$$

k is obtained in gravity units per foot, if the g_i are measured in gravity units and the h_i are measured in feet.

In practical field work it is always desired to obtain corrected gravity values as soon as possible after moving into a new prospect. On the other hand, the elevation correction constant cannot be determined accurately from too few stations. To see whether the observational material available is sufficient, or whether one should wait for more station readings, it is of value to know the probable error ϵ in k. ϵ can be determined by means of probability considerations:

$$\epsilon = 0.67 \sqrt{\frac{1}{n}\left[\frac{\sum_{i=2}^{N-1} g_i^2}{\sum_{i=2}^{N-1} h_i^2} - k^2\right]}, \tag{2}$$

where n is the number of terms in each sum. The value of k to be substituted in this formula should be calculated to 3 decimal places. In the sample computation form the practical arrangement of data and computation is shown. In field work a much larger number of stations would have to be used, of course, in order to make the probable error ϵ small.

[2] $\sum_{n=N_1}^{N_2} x_n$ is the abbreviation for the sum

$$x_{N_1} + x_{N_1+1} + \cdots + x_{N_2-1} + x_{N_2}.$$

$\sum_{i=2}^{N-1} (g_i + kh_i)^2$, for instance, means the sum of the squares

$$(g_2 + kh_2)^2 + (g_3 + kh_3)^2 + \cdots + (g_{N-1} + kh_{N-1})^2.$$

In the following we shall omit the limits at the $\sum$ symbol wherever they are obvious from the context.

To draw conclusions from the value of ϵ one must remember that there is a probability of 50%, 18%, 4% that the actual error is larger than ϵ, 2ϵ, 3ϵ, respectively. For instance, if the gravity at a given station must be known within 3 gravity units, and if there are hills on the prospect with a 100-foot relief, then k must be known with an accuracy of 0.03 unit per foot. If the chance of an error in k greater than 0.03 is not to exceed say 4%, the number of stations used in the calculation of k must be such as to make ϵ smaller or equal to 0.01.

In the method here described k is determined in a manner which will make the true gravity profile as "smooth" as possible. A definite mathematical meaning has been given to the word "smooth." The objection might be raised that our actual aim is rather to eliminate the correlation between corrected gravity and elevation. One actually finds the theoretically different formula (3)—see below—for k if one demands that the correlation factor between the quantities (g_i+kh_i) and the quantities h_i vanish. In practice, however, it has never been found necessary to use formula (3). The true gravity profile has always been so much more smooth than the topographic profile that smoothing out the gravity, using formula (1), was equivalent to eliminating correlation by means of formula (3). It is very easy to test the agreement between formulae (1) and (3), and the test has been carried out on the sample computation form, with the result that the formulae agree within 1/72 of the probable error.

The proof of formula (2) will be outlined in what follows. The error in h_i is neglected, since surveying work should always be carried out with sufficient accuracy. For the measured values g_i we assume the usual error distribution

$$p(g_i)dg_i = \frac{1}{\sigma\sqrt{2\pi}}\, e^{-(g_i+kh_i)^2/2\sigma^2} dg_i;$$

$p(g_i)dg_i$ is the probability of measuring a value of gravity between g_i and g_i+dg_i; σ is called the standard deviation. k can be considered as a weighted sum

$$k = \sum c_i g_i$$

with $c_i = \dfrac{h_i}{\sum h^2_i}$. According to a well known theorem of probability

calculus,[3] the standard deviation σ_s of this weighted sum is equal to

$$\sigma_s = \sigma\sqrt{\sum c_i^2} = \sigma\sqrt{\sum\left(\frac{h_i}{\sum h_i^2}\right)^2} = \frac{\sigma}{\sqrt{\sum h_i^2}}.$$

The standard deviation σ is determined from the observed values

$$\sigma = \sqrt{\frac{1}{n}\sum (g_i + kh_i)^2},$$

where n is the number of terms in the sum. If the stations lie on a continuous traverse, $n = N - 2$. Substituting this value for σ one obtains

$$\sigma_s = \sqrt{\frac{1}{n}\left[\frac{\sum g_i^2}{\sum h_i^2} - k^2\right]}.$$

The probable error ϵ in k is therefore

$$\epsilon = 0.67\sqrt{\frac{1}{n}\left[\frac{\sum g_i^2}{\sum h_i^2} - k^2\right]}.$$

The theoretically correct value of the elevation correction constant is obtained by choosing a value k' so as to eliminate the correlation between the quantities $g_i + k'h_i$ and the quantities h_i. The correlation coefficient[3] vanishes if

$$\sum [g_i + k'h_i - (\bar{g} + k'\bar{h})][h_i - \bar{h}] = 0$$

where

$$\bar{g} = \frac{1}{n}\sum g_i, \qquad \bar{h} = \frac{1}{n}\sum h_i.$$

We therefore have

$$\sum(g_i + k'h_i)h_i - (\bar{g} + k'\bar{h})n\bar{h} - \bar{h}n(\bar{g} + k'\bar{h}) + n(\bar{g} + k'\bar{h})\bar{h} = 0$$

or

$$\sum (g_i + k'h_i)h_i - n\bar{h}(\bar{g} + k'\bar{h}) = 0$$

which leads to

$$k' = -\frac{\sum g_i h_i - n\bar{h}\bar{g}}{\sum h_i^2 - n\bar{h}^2}. \tag{3}$$

[3] Cf. "Introduction to Mathematical Probability," by J. V. Uspensky, pp. 270, 339.

It can be made plausible from the definition of the g_i and h_i that in nearly all cases actually encountered the additional terms in numerator and denominator do not change the result.

SAMPLE COMPUTATION FORM

Sta. #i	g_i	h_i	g_ih_i	h_i^2	g_i^2
2	−70	+42	−2940	1764	4900
3	+74	−80	−5920	6400	5476
4	−30	+46	−1380	2116	900
5	+2	−4	−8	16	4
6	−4	+6	−24	36	16
7	−38	+60	−2280	3600	1444
8	+51	−78	−3978	6084	2601
			−16530	20016	15341

$$k = \frac{16530}{20016} = 0.826$$

$$\epsilon = 0.67\sqrt{\frac{1}{7}\left[\frac{15341}{20016} - 0.684\right]}$$

$$= 0.67\sqrt{\frac{1}{7}\left[0.766 - 0.684\right]}$$

$$= 0.072.$$

All gravity values are measured in gravity units; all elevations in feet.

The following computations are not required in field work but are carried out to show how the theoretically better formula (3) and the practical formula (1) give almost the same result.

$$k' = -\frac{\sum g_ih_i - n\bar{h}\bar{g}}{\sum h_i^2 - n\bar{h}^2} = -\frac{-16530 - 17}{20016 - 9} = 0.825$$

since

$$\bar{g} = \frac{1}{n}\sum g_i = -\frac{15}{7} \qquad \bar{h} = \frac{1}{n}\sum h_i = -\frac{8}{7}$$

$$n\bar{h}\bar{g} = 17 \qquad n\bar{h}^2 = 9.$$

SIMPLIFICATION OF TIDAL CORRECTIONS FOR GRAVITY METER SURVEYS*

JOSEPH L. ADLER†

ABSTRACT

Recent papers have called attention to the considerable effect of lunar and solar tidal forces on the vertical component of gravity but have given no instructions for the computation of this effect. Material published in English on this subject, so far as the author has been able to discover, does not present a rapid, practical method of computation which could be used economically as a matter of routine in gravimeter work. In this paper he attempts to analyze the degree of accuracy required in these computations, and develops a chart from which the tidal correction for any gravimeter observation in the United States can be obtained directly in less than a minute with an average error of less than 0.01 milligal.

Recent publications[1] have reported accurate measurements of the tidal force at certain points in the United States, and have called attention to its effect on gravimetric exploration. The purpose of this paper is to publish a convenient method of correcting for the tidal effect in a place readily available to practicing geophysicists. An incomplete method for computing the value of this force for a theoretically rigid earth is given by Heiland,[2] and a complete formula is given by Schweydar.[3] While Heiland's formula is simple, the tidal force is given as a function of the geocentric angle between the heavenly body and the point of observation, and no method is given for computing this angle from the data available to the computer; namely, the latitude and longitude of the station and declination and hour-angle of the heavenly body. Schweydar's equation is based on these four data, but since his purpose is to analyze the composite tidal wave and determine the frequency of all of its principal components, his formula is more involved than is necessary for our purpose.

* Presented at the Annual Meeting, Houston, Texas, April 2, 1941.

† Independent Exploration Co., Houston, Texas.

[1] Nettleton, L. L.: Geophysical Prospecting for Oil. McGraw-Hill, New York (1940), pp. 58–59.

Heiland, C. A.: Geophysical Exploration. Prentice-Hall, New York (1940), pp. 162–165.

Wolf, Alfred: Tidal Force Observations, GEOPHYSICS, vol. V (1940), pp. 317–320; and Tidal Gravity Observations, GEOPHYSICS, vol. VI (1941), pp. 81–83.

Wyckoff, R. D.: Trans. Amer. Geophysical Union; 17th Ann. Meeting (1936), pt. 1, pp. 46–56, and GEOPHYSICS, vol. VI (1941), p. 22.

[2] *Op. cit.*, p. 164.

[3] Schweydar, W.: Harmonische Analyse, p. 3.

The formula derived by Heiland[4] for the tidal force due to the sun and the moon at any point on a perfectly rigid earth's surface can be expressed as follows:

$$C' = -\frac{3krM_m}{2D_m^3}(\cos 2\alpha_m + \tfrac{1}{3}) - \frac{3krM_s}{2D_s^3}(\cos 2\alpha_s + \tfrac{1}{3}) \qquad (1)$$

where

C' = the vertical component of the tidal force on a rigid earth
k = the gravitational constant
r = the radius of Earth
$M_{(m,s)}$ = mass of Moon or Sun
$D_{(m,s)}$ = distance from Earth to Moon or Sun
$\alpha_{(m,s)}$ = geocentric angle between observation station and Moon or Sun.

Wolf[5] has demonstrated that while the tidal effect observed differs from the tidal force so computed for a perfectly rigid earth, due to the effect of the distortion of the earth itself by the tidal force, the mean square residuals of the computed force as compared with the tidal effect will be a minimum if the computed force is increased by 20%. This may be most simply accomplished by writing the above formula:

$$C = -\frac{3.6krM_m}{2D_m^3}(\cos 2\alpha_m + \tfrac{1}{3}) - \frac{3.6krM_s}{2D_s^3}(\cos 2\alpha_s + \tfrac{1}{3}). \qquad (2)$$

If we let

$$K_m = 2\left(\frac{3.6krM_m}{2D_m^3}\right) \qquad (3)$$

and

$$K_s = 2\left(\frac{3.6krM_s}{2D_s^3}\right) \qquad (4)$$

then

$$C = \tfrac{1}{3}(K_m + K_s) - (K_m \cos^2 \alpha_m + K_s \cos^2 \alpha_s). \qquad (5)$$

All of the quantities in the above equation (5) are constants except $\cos^2\alpha_m$ and $\cos^2\alpha_s$. The values of these constants are as follows:

$\frac{1}{3}(K_m + K_s)$ = 0.96 gravity units (i.e., tenths of milligals)
K_m = 1.978 gravity units
K_s = 0.902 gravity units.

[4] *Op. cit.*, p. 164.
[5] *Op. cit.*, vol. V, p. 320.

It now remains to express the variable $\cos^2\alpha$ as a function of the latitude of the observation station. If we let

θ' = Greenwich hour-angle of heavenly body
δ = declination of heavenly body
λ = longitude of observation station
ϕ = latitude of observation station

then

$$\cos^2 \alpha = [\cos \delta \cos \phi \cos (\theta' - \lambda) + \sin \delta \sin \phi]^2. \tag{6}$$

This identity is most easily derived by the operations of vectoral analysis. The angle $(\theta' - \lambda)$ is the local hour-angle of the heavenly body. The local hour-angle of the Sun is expressed directly by the local apparent time and that of the Moon may readily be determined from the local mean time with the aid of a chart constructed for the purpose, if the hour-angle interval from the Moon to the Mean Sun is known. This interval may be determined by subtracting the Moon's Greenwich hour-angle from that of the Sun and adding the equation of time, or by subtracting the Moon's Right Ascension from that of the Mean Sun. The latter is more practical as the Right Ascension of the Mean Sun and of the Moon varies so slowly that the same values can be used for several hours' observations.

Therefore, if we let

$$\theta = \theta' - \lambda \tag{7}$$

we can re-write equation (6)

$$\cos^2 \alpha = (\cos \delta \cos \phi \cos \theta + \sin \delta \sin \phi)^2. \tag{8}$$

Let us then substitute c_m and c_s for the last two terms of equation (5), letting

$$c_m = K_m(\cos \delta_m \cos \phi \cos \theta_m + \sin \delta_m \sin \phi)^2 \tag{9}$$

$$c_s = K_s(\cos \delta_s \cos \phi \cos \theta_s + \sin \delta_s \sin \phi)^2. \tag{10}$$

Equation (5) then becomes

$$C = \tfrac{1}{3}(K_m + K_s) - (c_m + c_s). \tag{11}$$

Charts may then be constructed for determining c_m or c_s as a continuous function of the local hour-angle and declination for any given latitude. If desired, the constant $\frac{1}{3}(K_m + K_s)$ may be neglected, as so doing merely shifts the datum, after the tidal correction is applied, from mean tide to minimum ebb tide. For the purpose of gravimetric surveys it is immaterial which datum is used. The sum of c_m and c_s may

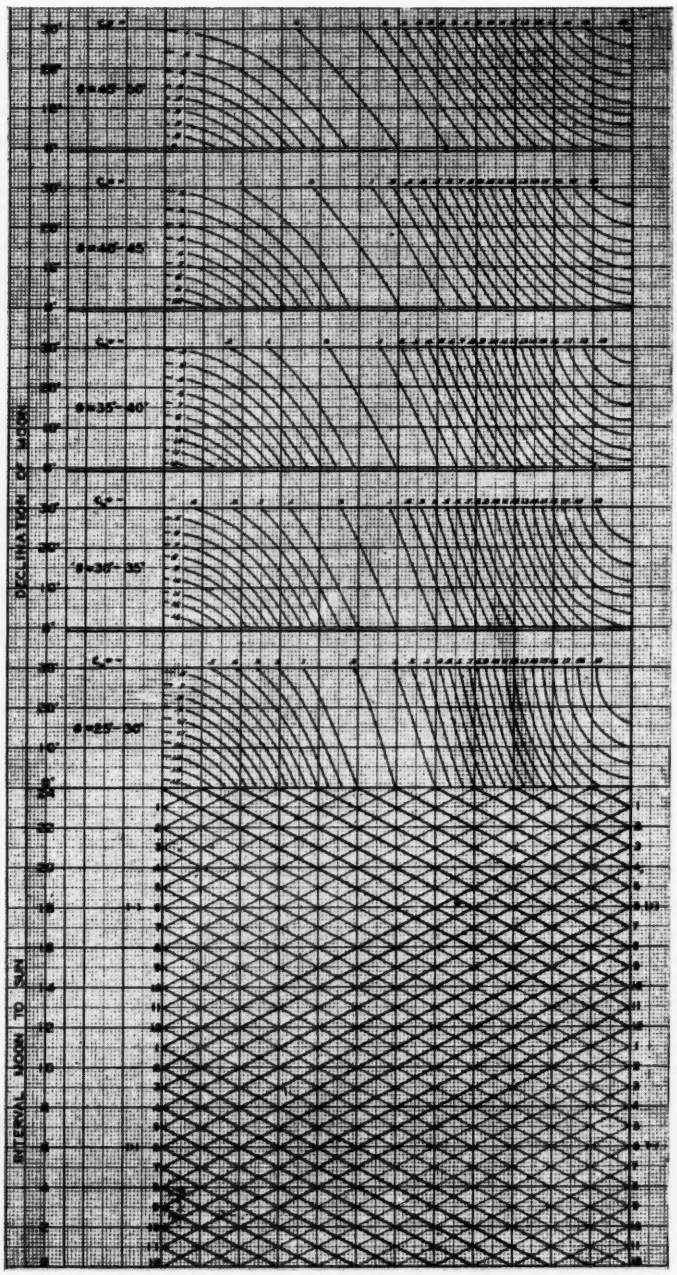

FIG. 1. Chart for determining lunar tidal correction in units. Note that in accordance with Eq. (2) these corrections are 20% greater than the actual tidal force because observations are on a non-rigid earth.

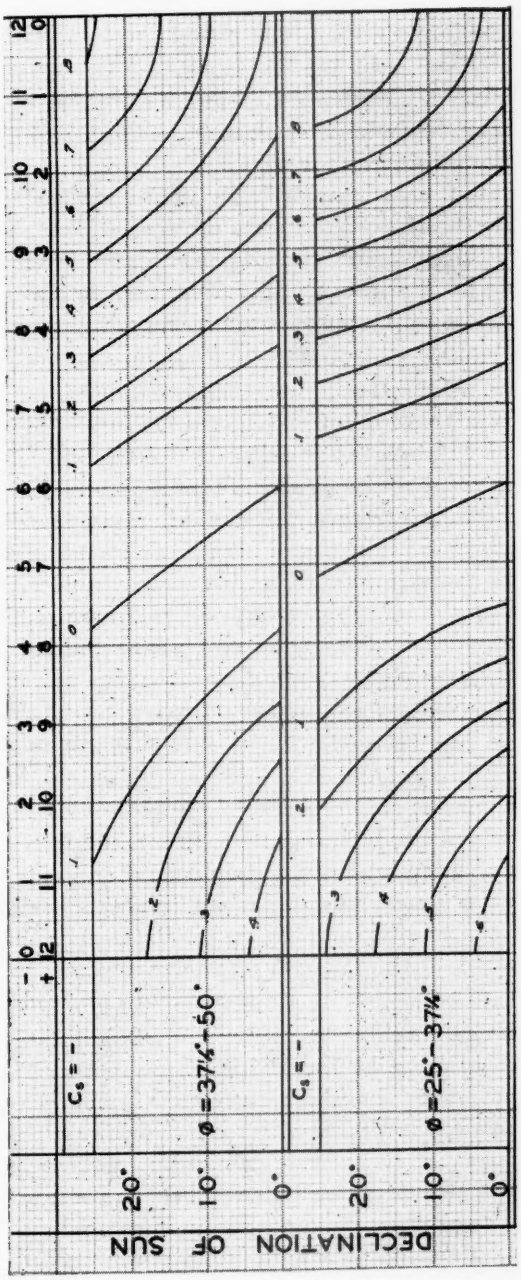

FIG. 2. Chart for determining solar tidal correction in units. Note that in accordance with Eq. (2) these corrections are 20% greater than the actual tidal force.

therefore be subtracted from the observed value of gravity and the effect of the tidal forces will thus be eliminated within the limits of accuracy required for geophysical exploration. The maximum error introduced by such a chart appears from the experimental work reviewed to be 0.2 gravity unit while the mean error would be considerably smaller than the observational error.

In order to make charts available for use over a reasonably wide range of latitude, however, it appears preferable from the practical standpoint to sacrifice some slight degree of accuracy, by using the values computed for a certain parallel of latitude to cover a zone on each side of that parallel. This procedure will involve a maximum total error of approximately 0.175 gravity unit if the observation station lies 2.5 degrees of latitude away from the parallel used to compute the Moon effect and 6.25 degrees from the parallel used to compute the Sun effect. For this reason, in preparing the charts shown in Figs. 1 and 2, latitude zones 5 degrees in width have been used for the Moon correction and zones 12.5 degrees in width have been used for the Sun correction. The ratio of the tidal force of the Moon to that of the Sun being about 2.2 to 1, a ratio of 1 to 2.5 in the widths of the respective zones used was considered the most practicable proportion. From this source, then, while the maximum possible error is about 0.175 unit, the average error is extremely small.

The declination of the Sun changes so slowly that the average value for several days can be used without introducing any appreciable error. The declination of the Moon, however, changes with relative rapidity, the maximum rate of change in declination being now about 10 minutes of arc per hour during that time of the month when the Moon lies near the celestial equator, and in certain years reaching about 15 minutes of arc per hour. Therefore, to use the same value for a period of more than twelve hours, before or after the time for which the declination was determined, may in future years cause a maximum error of 0.1 unit at spring tide. For this reason, in order to keep accumulated errors to a practical minimum it is advisable to look up the declination of the Moon for the midpoints of at least each six hour period during the time for which corrections are being made, thus keeping the maximum error from this source down to 0.025 unit.

The maximum variation of the tidal force per minute of time is 0.01 unit; therefore, if the correction is determined to the nearest multiple of five minutes local time, the error due to this cause will not exceed 0.025 unit. The difference in hour-angle between the Moon and the

Sun, which has heretofore been referred to as the interval from the Moon to the Mean Sun, varies at a fairly uniform rate of slightly less than 2 seconds of hour-arc per minute of time. To maintain the same maximum error as selected above, namely, 0.025 unit, the interval from the Moon to the Mean Sun should be known accurately to within 5 minutes of hour-arc. This could be accomplished by dividing the working day into 5-hour periods and determining the interval for the mid-point of each such period to be used throughout the period. In practice it has been found more satisfactory to use 6-hour periods.

Summing up the maximum error which could be accumulated coincidentally from all of the above sources, we obtain a total maximum error of 0.45 unit. The occasion on which such maximum cumulative error would occur is so rare as to lie outside of the realm of a practical probability. The probable total error due to the above computation is obviously much less than the probable observational error which on the more accurate gravimeters is somewhat less than 0.25 unit, the maximum observational error being more than twice that amount. Also, if a maximum surveying misclosure of one foot in elevation is permitted, if that misclosure were due to an undetected gross error of one foot, after distribution around the traverse the average elevation error per station would be one-half foot, which corresponds to 0.47 gravity unit. If the gross error were made near the station, the corrected elevation at that point might be in error nearly a foot, producing an error in gravity of nearly one unit. Actually, of course, the distribution of cumulative surveying errors aggregating less than one foot reduces the net error at any station to considerably less than the instrumental error.

Thence it is seen that the errors involved in computation of tidal corrections by means of charts such as those illustrated in Figs. 1 and 2, when drawn to a suitable scale, are less than the other errors involved in gravimeter surveys. The total effect of the tidal force itself, on the other hand, at periods of spring tide has been calculated[6] to amount to as much as 3.4 units at Pittsburgh, Pennsylvania. Maximum correction developed on the chart is about 2.9 units for that latitude. Detailed gravimeter surveys are in many cases contoured on an interval of 2 units. In such cases a drift curve determined by frequent check readings of base stations is relied upon to remove the tidal effect.

[6] Wyckoff, R. D., *op. cit.* (1936), and Heiland, C. A., *op. cit.*

The result of this procedure is to produce an erratic looking drift curve at times of spring tide. Owing to the fact that at some times the instrumental drift will be in the same direction as the tidal drift and at others will be in the opposite direction, a composite drift curve drawn on the basis of repeat observations only, without taking cognizance of the periodicity of the tidal drift, may be inaccurate by more than 0.5 unit if the repeat observations are made at intervals of four hours. This is one reason why base stations are often resorted to every two hours. The writer believes, however, that if by means of a chart such as is described herein, the computer would construct a tidal drift curve for the day and use it to correct all readings for tidal drift, most modern gravimeters would show such regular residual drift due to other causes that a number of repeat readings at base stations could be eliminated.

To make such corrections would require about an hour of the computer's time each day; therefore it would be impractical to use them under ordinary conditions in terrain where numerous roads permit the meter operator to re-read base stations every two hours without appreciable loss of time. But in country with few or no roads where it is impractical to check in on base stations oftener than once a day, or even less often as in the case of reconnaissance surveys as sometimes conducted in unsettled countries, such tidal corrections will greatly increase the accuracy of a gravimetric survey. In territory where readings on base stations may quickly be made whenever desirable it might still be profitable to make the tidal correction whenever the drift curve appears notably erratic, so that the operator could determine whether the erratic drift were due to spring tides or to improper functioning of the gravimeter.

The method of constructing the charts should be evident from the principles set forth in the foregoing after examining the small scale reproduction of the charts illustrated in Figs. 1 and 2. The following instructions for efficient use of the charts might prove useful, however.

1. Look up in the American Nautical Almanac[7] for the year in question the Declination of the Sun (δ_s) for the day to the nearest degree; the Declination of the Moon at 9:00 A.M. Standard Time, properly converted to Greenwich time, (δ_{m9}) to be used during the morning hours; the Right Ascension of the Moon (RA_{m9}) at the same time;

[7] Published by United States Naval Observatory, Washington, D. C.; sold by Superintendent of Documents, Washington, D. C., price 55 cents.

the Declination of the Moon (δ_{m3}) and Right Ascension of the Moon (RA_{m3}) at 3:00 P.M., Standard Time, to be used during the afternoon hours; and the Right Ascension of the Mean Sun (RA_s) at noon Standard Time.[8]

2. Obtain Interval from Moon to Sun to be used during morning hours (I_9) by subtracting RA_s from RA_{m9}, and Interval to be used during afternoon hours (I_3) by subtracting RA_s from RA_{m3}. If either difference is negative, add 24^h to it algebraically.

3. Lay a straight edge along the horizontal line in Fig. 1 representing the interval obtained under Instruction 2 above.

4. Lay another straight edge along the horizontal line in the proper latitude zone in Fig. 1 representing the Declination of the Moon (δ_m). The latitude zone is determined by the latitude of the gravity stations.

5. Note the intersection of each Local Time hour line (oblique lines) with the lower straight edge and trace a vertical line from each intersection to the upper straight-edge. At the intersections of the vertical lines with the upper straight-edge, read directly and note the correction for the effect of the Moon (c_m) for each full hour of Local Time. Note that P.M. hours are given the same algebraic sign as the Moon's Declination while A.M. hours are given the opposite sign.

6. Now lay a straight edge along the line representing the Declination of the Sun (δ_s) in the proper latitude zone in Fig. 2 and note the intersection of the vertical lines representing each hour of Local Time with the straight-edge. Read directly and note at each such intersection the value of the correction for the effect of the Sun (c_s) for each hour of Local Time. In this case, also, P.M. hours are given the same algebraic sign as the Sun's Declination and A.M. hours are given the opposite sign.

7. Add the Sun correction (c_s) to the Moon correction (c_m) for each hour of Local Time.

8. For each full hour of Local Time at the center of the area in which the day's work was done, determine the equivalent Standard Time by subtracting from the Local Time one minute for each 15 minutes of longitude east of the Standard Time meridian or adding

[8] To determine the above data accurately all times must of course first be converted to Greenwich Civil Time, but the Right Ascension of the Mean Sun at noon Standard Time for anywhere in the United States may be determined with sufficient accuracy by adding $12^h\ 3^m$ to Sidereal Time of 0^h Greenwich Time, if latter is less than 12^h, or subtracting $11^h\ 57^m$ if more than 12^h.

one minute for each 15 minutes of longitude west of the Standard Time meridian.

9. Using the Standard Times obtained under Instruction 8 as abscissa values, lay off the corresponding sums of the Sun and Moon corrections (c_s+c_m) on the ordinate axis on coordinate paper of suitably large scale and connect the points with a smooth curve. The correction to be subtracted from the observed gravity value can then be determined from this curve for any Standard time of observation.

10. If work done before 6 A.M. or after 6 P.M. is to be corrected, the values of δ_m and RA_m should be determined for 9:00 P.M. and 3:00 A.M. and RA_s should be determined for midnight[9] and the respective values of δ_m and I obtained from these data for 9:00 P.M. and 3:00 A.M. should be used for evening and early morning corrections respectively.

The writer wishes to acknowledge his indebtedness to Mr. C. T. MacAllister and Mr. C. H. Broussard for their assistance in the computation and preparation of the charts and to Dr. Morton Mott-Smith for supplying valuable references.

[9] Right Ascension of the Mean Sun for any point in the United States at midnight can be determined with sufficient accuracy by adding $12h\ 1m$ to Sidereal Time of $0h$ Greenwich Civil Time for the following day if the Sidereal Time of $0h$ G.C.T. is less than $12h$, or subtracting $11h\ 59m$ if it is more than $12h$.

TEST OF A QUANTITATIVE MOUNTAIN BUILDING THEORY BY APPALACHIAN STRUCTURAL DIMENSIONS*

THOMAS A. ELKINS†

ABSTRACT

A mathematical paper by Ross Gunn (Journal of the Franklin Institute, volume 224, pages 19–53, 1937) gives a mountain building theory which makes possible the calculation of certain structural dimensions in terms of thickness and strength of the geologic elements involved. The present paper applies various formulae from Gunn's paper to the calculation of width and amplitude of folds, to basin widths and depths, and to mountain heights of the Appalachian Mountain system. The numerical values resulting are in surprisingly good agreement with previously published values measured or estimated from the known geology of the area. A brief discussion is also given of the theoretical interpretation, by Gunn's theory, of the large isostatic gravity anomaly here as due to possible crustal stress.

INTRODUCTION

The large amount of geological and geophysical data which was collected in connection with the Appalachian Mountains gravimeter profile run by the Gulf Research & Development Company staff (Nettleton, 1941)[1] presented an unusual opportunity for a practical test of the mountain building theory of Ross Gunn (Gunn, 1937), a theory which does not seem to have received, from geologists, the attention it deserves.

The remarkable feature of Gunn's theory is that it leads to numerical results which can be tested against nature. Such a check cannot be made for the usual run of purely geological theories which are descriptive rather than numerical. For a complete account of this theory we must refer the reader to the original paper (Gunn, 1937). Here we shall merely list the formulae of Gunn's paper which we shall apply.

LIST OF FORMULAE FROM GUNN'S PAPER

In this list the notation is as far as possible identical with that of Gunn's paper.

Formula (1) can be derived from Gunn's equation (4) by setting M_e equal to zero. It states that an isostatic gravity anomaly may be an indication of stress in the earth's crust.

* Presented at the Annual Meeting, Houston, April 2, 1941.

† Gulf Research & Development Co., Pittsburgh, Pa.

[1] References in this form are listed at the end of the paper.

$$S_v = -\frac{g\Delta g}{2\pi\gamma}, \tag{1}$$

where S_v is the vertical stress,
g is the acceleration due to gravity at the earth's surface,
Δg is the isostatic gravity anomaly, and
γ is the gravitational constant.

Formulae (2), (3) and (4) are results of Gunn's theory of the building of major mountains by the formation of a geosyncline and its subsequent compression.

Formula (2), illustrated in Fig. 1, can be derived from equation (18) of Gunn's paper.

$$W = \frac{\pi}{2}\left[\frac{ET^3}{3(d_0 - d)g}\right]^{1/4}, \tag{2}$$

where W is the approximate width of a downward deformation of the earth's crust caused by compressive force and thrust faulting,
E is Young's modulus of elasticity for the earth's crust,
T is the thickness of the earth's crust,
d is the density of the near surface sedimentary material,
d_0 is the density of the basement or non-sedimentary crust, and
g is the acceleration due to gravity at the earth's surface.

Formula (3), also illustrated in Fig. 1, can be derived from equation (19) of Gunn's paper.

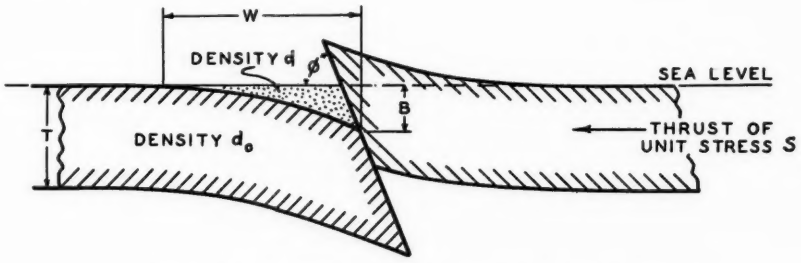

FIG. 1. Formation of geosyncline by compressive stress.

$$B = 2\left[\frac{3T(d_0 - d)g}{E}\right]^{1/4} \frac{S\cos\phi\sin\phi}{(d_0 - d)g}, \tag{3}$$

where B is the approximate depth of the downward deformation of the earth's crust caused by compressive force and thrust faulting,
E is Young's modulus of elasticity for the earth's crust,
T is the thickness of the earth's crust,
d is the density of the near surface sedimentary material,
d_0 is the density of the basement or non-sedimentary crust,
g is the acceleration due to gravity at the earth's surface,
S is the horizontal compressive stress which is responsible for the deformation of the earth's crust, and
ϕ is the angle of the fracture plane of the fault with the horizontal.

Formula (4), illustrated in Fig. 2, is from equation (30) of Gunn's paper.

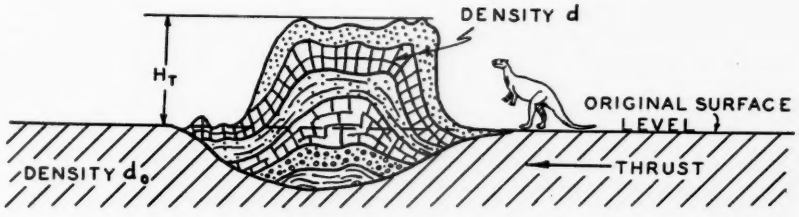

FIG. 2. Formation of a major mountain.

$$H_T = H \frac{\beta w_1}{w_2} \frac{d_0 - d}{d_0}, \tag{4}$$

where H_T is the height of a mountain above the original continental level,
H is the original maximum thickness of the sedimentary layer which is folded to form the mountain,
β is the ratio of the average to the maximum initial thickness of the sedimentary layer,
w_1/w_2 is the ratio of the initial length of the sedimentary layer in the direction of folding to the final length,
d is the density of the near surface sedimentary material, and
d_0 is the density of the basement or non-sedimentary crust.

Formulae (5) and (6) are results of Gunn's theory of formation of minor mountains by the folding of the upper layers of the earth's

crust. No erosion or sedimentation after folding is taken into consideration in these formulae.

Formula (5), illustrated in Fig. 3, is equation (24) of Gunn's paper.

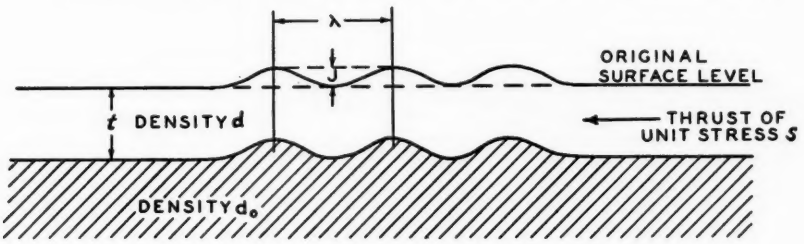

FIG. 3. Formation of folds by compression.

$$\lambda = 2\pi \sqrt{\frac{st}{dg}}, \tag{5}$$

where λ is the distance between the crests of the folded sediments,

s is the horizontal compressive stress which is responsible for the folding,

t is the initial thickness of the layer which is folded,

d is the density of the near surface sedimentary material, and

g is the acceleration due to gravity at the earth's surface.

Formula (6), also illustrated in Fig. 3, is equation (31) of Gunn's paper.

$$J = t \frac{w_1 - w_2}{w_2} \frac{d_0 - d}{d_0}, \tag{6}$$

where J is the height of a mountain formed by folding,

t is the initial thickness of the layer which is folded,

d is the density of the near surface sedimentary material,

d_0 is the density of the basement or non-sedimentary crust, and

w_1/w_2 is the ratio of the initial length of the sedimentary layer in the direction of folding to the final length.

VALUES OF THE PHYSICAL CONSTANTS USED

In the formulae above certain physical constants occur, some of which can only be estimated from rather scanty data. We shall dis-

cuss most of these in this section. We do not always use the numerical values of Gunn's paper.

The gravitational constant, γ, will be taken as 6.66×10^{-8} c.g.s.u. The acceleration due to gravity at the earth's surface, g, will be taken as 980 gals, which is sufficiently close to the actual values for our purpose.

The thickness of the earth's crust, T, will be taken as 100 km (about 62 miles), which value is consistent with the evidence from isostasy. Young's modulus of elasticity, E, for the earth's crust will be taken[2] as 12×10^{11} dynes/cm^2. For S, the compressive stress responsible for the deformation of the earth's crust, we shall usually take 10^9 dynes/cm^2, which is an estimate of the limiting value which would cause fracture or flow of the earth's crust.[3] Theoretically, S may vary from zero to this maximum value but for simplicity we shall keep it fixed, except in two special cases, for which the changed value will be specifically stated.

The density, d, of the present near-surface sedimentary material is taken as 2.67; the density, d_0, of the basement or non-sedimentary crust is taken as 2.87. These values are based on the results of density profiles from the gravimeter data (Nettleton, 1941). When younger sedimentary material is involved, a different value will be used for d. When this is done, the fact will be specifically stated.

In the study of Appalachian folding, we shall be interested in the ratio w_1/w_2, the ratio of the initial length of a sedimentary layer in the direction of folding to the final length. We shall need only the average and the maximum values of this ratio for the Appalachian Mountains. Ernst Cloos has measured the shortening for one hundred forty-three sections in the anthracite area of eastern Pennsylvania (Cloos, 1940). In Cloos' notation $w_1/w_2 = a/b$. If we eliminate sections shorter in length than 2500 ft. which, as Cloos says, may be misleading, the greatest percentage reduction, 100 $(1\text{-}b/a)$, in his Table 1 is 60. This value corresponds to $w_1/w_2 = 2.5$. A percentage reduction of 33 per cent is regarded by Cloos as a good average figure for the eastern Appalachians and corresponds very nearly to $w_1/w_2 = 1.5$. Accordingly

[2] According to B. Gutenberg, E varies from 7×10^{11} to 15×10^{11} dynes/cm^2 in the first 100 km of the earth's crust (Gutenberg, 1939a). Our adopted value is intended to be an average one.

[3] According to B. Gutenberg, S is slightly more than 10^9 dynes/cm^2 near the surface for most types of rock (Gutenberg, 1939b). The variation with depth is a difficult question; from the evidence assembled by Gutenberg, which includes work by Barrell and Jeffreys, our adopted value is probably of the right order of magnitude.

we shall use $w_1/w_2 = 1.5$ as the average and $w_1/w_2 = 2.5$ as the maximum value.

For convenience of reference we tabulate alphabetically in Table 1 the notation used in this paper, together with the adopted values of physical constants.

TABLE 1

Notation and Values of Physical Constants

Symbol	*Meaning*	*Adopted Value*
B	Approximate depth of downward deformation of earth's crust caused by compressive force and thrust faulting.	
d	Density of near surface sedimentary material.	2.67, except when noted
d_0	Density of basement or non-sedimentary crust.	2.87
E	Young's modulus of elasticity for the earth's crust.	12×10^{11} dynes/cm^2
g	Acceleration due to gravity at the earth's surface.	980 gals
H	Original maximum thickness of a sedimentary layer which is folded to form a mountain.	
H_T	Height of a mountain above the original continental level.	
J	Height of a mountain formed by folding.	
S	Horizontal compressive stress responsible for a deformation of the earth's crust.	10^9 dynes/cm^2, except when noted
s	Horizontal compressive stress responsible for folding.	
S_v	Vertical stress.	
T	Thickness of the earth's crust.	100 km
t	Initial thickness of a layer which is folded.	
W	Approximate width of a downward deformation of earth's crust caused by compressive force and thrust faulting.	
w_1/w_2	Ratio of the initial length of a sedimentary layer in the direction of folding to the final length.	Average value, 1.5; Maximum value, 2.5
β	Ratio of the average to the maximum initial thickness of a sedimentary layer.	
γ	Gravitational constant.	6.66×10^{-8} c.g.s.u.
Δg	Isostatic gravity anomaly.	
λ	Distance between crests of folded sediments.	
ϕ	Angle of the fracture plane of a fault with the horizontal.	

THE APPALACHIAN GEOSYNCLINE

We now begin the detailed application of Gunn's theory to the Appalachian Mountains and first discuss the formation of the Appalachian geosyncline. We shall restrict our computations to the Paleozoic geosyncline, for which stage numerical data first begin to be available. By Gunn's theory, the approximate width, W, of a synclinal deformation of the earth's crust, produced by compressive force (from the east in our case[4]) acting through the entire thickness of the

[4] This direction is in conformity with the geological evidence, but it should be mentioned that the mathematical theory we use in this paper is independent of the direction of force and would yield the same formulae for a thrust from the opposite direction.

earth's crust and by subsequent faulting, is found from formula (2). We shall compute three cases. For case 1 we assume that there is yet no sedimentation in the syncline; then $d=0$ and $W=$ about 305 km (about 190 miles) for the numerical values of the other constants as given above. For case 2 we assume that the geosyncline is filled with water; then $d=1.0$ and $W=$ about 340 km (about 211 miles). Case 3 represents the final stage of sedimentation; $d=2.67$ and $W=$ about 594 km (about 369 miles). The values of d used cover the complete range of reasonable densities and the values of W for cases 1 and 3 are the minimum and maximum values possible for the assumed values of the other constants.

We now compare these calculated values with the estimates of the actual width of the Appalachian geosyncline based on geologic evidence. Bailey Willis and Robin Willis say that it was "in general about 100 miles wide" (Willis and Willis, 1934, page 71), while Paul H. Price assumes a present approximate width of 300 miles (Price, 1931, page 36). The computed values above are thus probably of the right order of magnitude.

From Gunn's theory, the approximate depth, B, of the geosyncline is given by formula (3). We shall take $\phi=45°$ and compute B for the same three cases for which W was computed. For case 1, $d=0$ and $B=$ about 1.83 km (about 1.1 miles). For case 2, $d=1.0$ and B now $=$ about 2.52 km (about 1.6 miles). For case 3, $d=2.67$ and B now $=$ about 13.50 km (about 8.4 miles). The values of d used cover the complete range of reasonable densities and the values of B for cases 1 and 3 are the minimum and maximum values possible for the assumed values of the other constants.

We shall now see how these values of B agree with the actual known geology. We are unable to check case 1 ($d=0$, no sedimentation) because of lack of survey data at that time. Perhaps all we should expect from the computation is a basin deep enough to make possible the shallow sea and sedimentation history of a geosyncline. The computed value of B (about 1.1 miles) is adequate, perhaps more than adequate, even when account is taken of the fact that this value is the maximum and that the greater extent of the basin would have a lesser depth.[5] However, we may also make use of Gunn's suggestion, which follows from his theory concerning the origin of tangential stresses in the earth's crust,[6] that the value of S at the beginning of

[5] Fig. 2 of Gunn, 1937, is a graph of the cross section of the downwarp produced. From it one finds that about 50% of the basin area will be above a level which is only three-tenths of the maximum depth.

[6] See Gunn, 1937, pp. 51–52.

the geosynclinal formation may be less than 10^9 dynes/cm^2. In an illustrative example shown in Fig. 3 of his paper, he uses the value 3×10^8 dynes/cm^2 for S. If we use this value in case 1 instead of 10^9 dynes/cm^2, we find that B = about 0.34 mile. In this case about half the basin area would be at a depth of 0.10 mile or less, an ideal arrangement for sedimentation.[7]

For case 2 (d = 1.0, geosyncline filled with water), we found that B was about 1.6 miles, a value about 50% greater than before. This case is closer to reality than case 1, since the basin would probably fill with water as soon as it was formed. If we again use the value 3×10^8 dynes/cm^2 for S instead of 10^9 dynes/cm^2, we see that the basin conditions would again be suitable for sedimentation, since the depths would be increased only about 50% of the values for case 1.

For case 3, which is intended to yield the maximum possible depth, we found about 8.4 miles. This agrees very well with the estimate by Price of 8 miles as the maximum depth of the geosyncline (Price, 1931, Fig. 6). Charles Schuchert gives a total of 55,000 ft. (about 10.4 miles) of Paleozoic strata (in southern Pennsylvania and Maryland) as the maximum value for the Appalachian geosyncline (Schuchert, 1931). This latter figure may be high for our purpose since it combines thicknesses that may not all occur at the same locality. It thus seems that the computed value is reasonable.

For intermediate stages in the history of the geosyncline we could compute values of W and B by using an appropriate average value of d. To estimate such an average value would require detailed information as to original composition of individual strata and the effects of compaction, information which is not available. Such intermediate density values would necessarily yield values of W and B intermediate to the minimum and maximum values we have computed for cases 1 and 3, which fact fits well into the geologic picture of a generally widening and deepening geosyncline. The formulae apply to a static condition at some final stage of development and make as it were a "snapshot" of the geosyncline;[8] a continuous dynamic consideration

[7] The use of a smaller stress than the assumed strength of the rocks might be questioned here on the basis that the faulting which initiates the geosyncline would not occur unless the breaking or crushing strength of the crust is reached. This objection might be answered by assuming that the site of the Paleozoic Appalachian trough was a preexisting zone of weakness, such as might occur, for example, if the crust were made of weak layers, perhaps broken or faulted, which would break under a lesser stress.

[8] It is worth noting in this connection that when d is greater than zero (that is, when sediments are actually present), formulae (2) and (3) involve the requirement

of the process has so far not been developed. Thus there is nothing in the theory which prevents the introduction of many known geologic details. For example, we might reasonably expect variations in S over long geologic periods, which variations might cause repeated exposure and flooding of the basin region, or lead to erosion of previously deposited sediments (Gunn, 1937, page 38).

THE MAJOR APPALACHIAN MOUNTAINS

We now assume that the geosyncline discussed above is folded by compressive stress from the east.[4] From Gunn's theory the height, H_T, of a mountain formed by such a process, taking isostatic adjustment into account, is given by formula (4). To find the maximum value of H_T we shall use for H the maximum computed value of B (that for case 3) and the maximum value of w_1/w_2, which is 2.5. For β we shall use two values: $\frac{1}{2}$, which corresponds to a prism of sediments of triangular cross-section; and 1, which corresponds to the case of faulting at both ends of the geosynclinal basin. For $\beta=\frac{1}{2}$ the computed maximum value of H_T is about 1.18 km (about 0.73 mile), for $\beta=1$ about 2.35 km (about 1.46 miles).

The maximum height of the original Appalachian Mountains, after erosion is taken into account, may have been, according to Schuchert, from 2 to 3 miles (Schuchert, 1924, page 427). The computed values of H_T are low, but of the right order of magnitude.

POSSIBLE CRUSTAL STRESS

Gunn suggests that apparently excessive isostatic gravity anomalies may be the result of crustal stress. The relation between the vertical stress (positive downward), S_v, and the isostatic gravity anomaly, Δg, is given by formula (1). The minimum gravity value on the isostatic gravity profile across the Appalachian Mountains (Nettleton, 1941) occurs at station 20 and is -63 milligals. From formula (1) we find that S_v is about 1.48×10^8 dynes/cm^2. This is a fairly high value and might possibly be regarded as an indication of unstable crustal conditions were it not that this area is considered to be "dead" geologically. However, the lack of coincidence of the isostatic gravity anomaly and the presumed sedimentary basin obviously suggests that the gravity profile is of greater complexity than it should be if it were due only to a simple basin in isostatic equilibrium.

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that the geosyncline be completely filled with the sediments to the level of the surface of the undisturbed earth.

Since the problem appears to be one of gravity interpretation rather than of mountain building, we shall merely refer the reader to the thorough discussion by L. L. Nettleton (Nettleton, 1941).

MINOR APPALACHIAN FOLDING

We have seen above that the major Appalachian Mountains (the eastern section) may have been formed from a geosyncline produced by a compressive force acting through the entire thickness of the earth's crust (here taken as 100 km). However, the western section has been long recognized as being distinctively different and, in fact, it is a zone of minor folding (Sherrill, 1941, page 416). We shall consider that it may have been caused by compressive force acting through comparatively thin upper layers of the crust.[9] The formation of such "pressure-ridges" is also taken into account in Gunn's theory. Since folding here is supposed to have extended over a very long period, it is not illogical to consider the minor and major folding separately, since they may have actually occurred at different times.

(*a*) *Horizontal distance between folds.*

From formula (5) we may calculate the distance, λ, between the crests of the folded sediments. The formula involves two quantities, s and t, which can only be estimated; our calculation of λ thus is rather tentative. For the compressive stress, s, which causes the folding we shall use 10^8 dynes/cm^2 since we have already used a value of 10^9 dynes/cm^2 as the breaking or flowing stress. There is very little geologic evidence as to the value of t. From a study of published geologic profiles for the Appalachians, an average value of 5 miles seems reasonable, except for the very sharp folding east of Scrub Ridge where a value of 2 miles was estimated.[10] That values as low as these are not unreasonable may be inferred from the evidence gathered by Walter H. Bucher (Bucher, 1933, pages 151–157). Further, we have mentiond that Price estimates the maximum thickness of the geosyncline as 8 miles, a value which was closely checked by our theoretical calculations. An average value of 5 miles is thus quite reasonable. From

[9] This is here equivalent to the assumption that the basement, which is inferred from well data to be comparatively shallow, does not take part in the folding. Alternatively, the agreement of the calculated and the observed values may be regarded as an indication of the correctness of the assumption.

[10] The region east of Scrub Ridge is doubtless in the area of major Appalachian uplift. Still the basement conditions are such that we may apply, at least tentatively, the same treatment as for the western Appalachian area.

formula (5) we find that λ = about 7 miles for $t = 5$ miles and about 4 miles for $t = 2$ miles. These computed values are certainly of the right order of magnitude as we see from Table 2. Confirmation is given to the calculated values by R. E. Sherrill, who states that the anticlines in southwestern Pennsylvania average about 8 miles in width, with a range of about 4 to 12 miles (Sherrill, 1934, page 231). Also, George H. Ashley gives a width of 14 miles for the Chestnut Ridge anticline (Ashley, 1908).

Since there is so much data available on the spacing of the Appalachian folds, it seems worth while to reverse the process and use formula (5) to compute values of s and t from observed values of λ.

TABLE 2

Values of Compressive Stress, s, and Thickness of Folded Layer, t, as Computed from Distance, λ, between Crests of Folded Sediments

Location of Data	λ	s for $t = 5$ miles (2 miles for item c)	t for $s =$ 10^9 dynes/cm^2
Using data from geologic cross-section for Appalachian Mountain gravimeter profile (Nettleton, 1941).			
(a) Folding west of Allegheny Front.	8 miles	1.37×10^8 dynes/cm^2	0.68 mile
(b) Folding east of Allegheny Front (up to Scrub Ridge).	6	0.77	0.38
(c) Sharp folding east of Allegheny Front.	2	0.21	0.04
Using data from "Geologic map of Pennsylvania," Department of Internal Affairs, 1931, and from Leighton, 1939.			
(d) Folding west of Allegheny Front.	9	1.73	0.86
(e) Folding east of Allegheny Front.	10	2.13	1.07
Using data from "Geologic map of West Virginia by the West Virginia Geological Survey," 1932, Scale 1:500,000.			
(f) Folding west of Allegheny Front.	14	4.18	2.09
(g) Folding east of Allegheny Front.	11	2.58	1.29

The results are summarized in Table 2, which lists the average observed values of λ (to the nearest mile) and the computed values of s and t. Naturally we cannot compute both s and t from formula (5) for a given value of λ; we must set a value for either one in order to compute the other. The values of t were computed by setting s equal to 10^9 dynes/cm^2, the assumed failure stress; these values of t are

therefore minimum values, that is, the actual thickness of crust folded is greater. All of the values of s were computed for $t=5$ miles, except in the case of item c for which the value $t=2$ miles was used. The profiles studied were approximately perpendicular to the strike of the mountains. The computed values of s and t seem generally to be of the right order of magnitude, but it would probably be unsafe to draw any conclusions from the areal differences between the values.

(*b*) *Height of folds.*

From formula (6) we may calculate the height, J, of a mountain produced by the folding of a surface crust, taking isostatic adjustment into account. To find the maximum value of J we shall use the maximum value of w_1/w_2 (2.5) and the value 8 miles for t, which value, as we have mentioned before, is given by Price and is also consistent with our theoretical calculations. It is true that Bucher, in discussing some work of R. T. Chamberlin, computes a value for t of 13.2 miles (Bucher, 1933, pages 151–153), but this value is for a section of much smaller value of w_1/w_2. Using $w_1/w_2=2.5$ and $t=8$ miles, we find that the maximum value of J is about 0.84 mile.

It may be unfair to use maximum values for both t and w_1/w_2. We have therefore made two more computations, in which we use the maximum value for one parameter and an average value for the other. For $w_1/w_2=2.5$ and $t=5$ miles, $J=$about 0.52 mile. For $w_1/w_2=1.5$ and $t=8$ miles, $J=$about 0.28 mile.

We shall now see how these heights agree with the known geology. The values of J are theoretical heights above the original surface level of the sediments and in comparing them with present Appalachian heights above sea level we must remember that there has since occurred both erosion and upward warping of the entire Appalachian tract. The two processes will work in opposite directions and perhaps the best we can do is to compare the computed values directly with the present values above sea level. The average elevation of the Appalachian Mountains has been estimated by Harold Jeffreys as 1000 meters (about 0.62 mile) (Jeffreys, 1924, page 136). We would probably expect the average value for the western section of less intense folding to be lower than this. The computed values of J are thus reasonable.

Another measure of uplift is found by taking the differences between maximum elevations of anticlines and minimum elevations of adjacent synclines. For example, these differences for the Grapeville

anticline and the Irwin-Port Royal and Greensburg synclines are 925 ft. (about 0.18 mile) and 800 ft. (about 0.15 mile), respectively, according to Henry Leighton (Leighton, 1939, page 17). These values are of the same order of magnitude as the theoretical value of J for $t = 5$ miles and $w_1/w_2 = 1.5$, which is about 0.17 mile.

More confirmation of the computed values on this basis is given by Sherrill who states, in a discussion of the northern Appalachian foreland folds (Sherrill, 1934, page 226):

"Although some of the anticlines rise in places to heights of 2,500 feet or more above the adjoining synclines, . . . folds 300–800 feet high, . . . are more numerous."

Also, Ashley gives a height of 740 feet (about 0.14 mile) for the Chestnut Ridge anticline (Ashley, 1908).

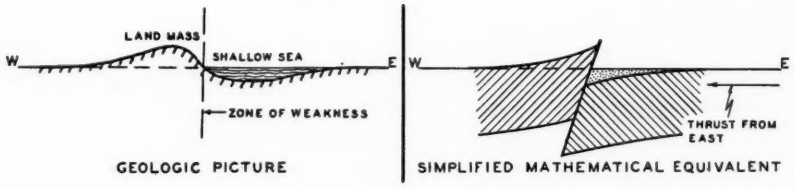
HYPOTHETICAL HISTORY OF APPALACHIAN MOUNTAINS

In order to handle the mountain building problem mathematically it was necessary to idealize the geologic structures to a considerable extent. Fig. 4 shows the geologic structure and its approximate mathematical equivalent at various stages in the history of the Appalachian region. These stages have been highly generalized and are rather speculative, especially in the early history, for which geologists hold conflicting opinions. We have followed the theories of Arthur Keith closely for the first three stages (Keith, 1923). The history is presented merely as an illustration to show how many of the known geological details can be fitted into the framework of the mathematical theory. Since this theory, as we mentioned before, is an idealized "static" theory, it is to a certain extent independent of the order of discrete stages of development or other dynamic considerations which are not taken into account in the mathematical development. Thus it is quite probable that other hypothetical histories of the Appalachian Mountains could also be fitted into the mathematical framework.

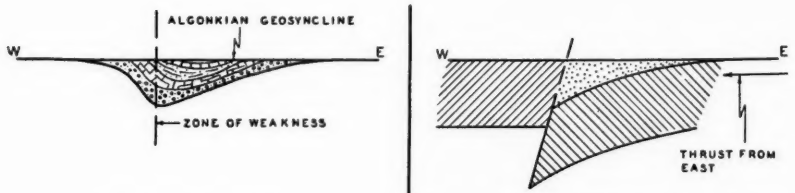
CONCLUSION

It is believed that the calculations above show that Gunn's theory of mountain building provides a good quantitative basis for the history and development of the Appalachian Mountains.

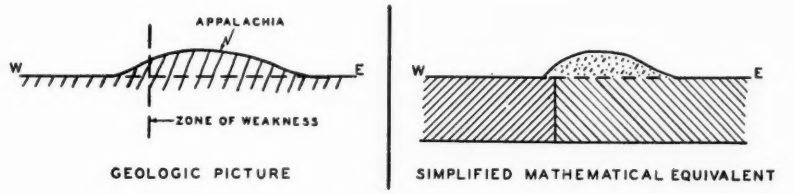
The processes of mountain building which we have described are dependent on a compressive force acting through the crust of the earth. It is worth mentioning definitely that the equations and calculations of this paper are independent of the source of the compressive



1. ALGONKIAN TIME. LAND ON WEST, SEA ON EAST. ZONE OF WEAKNESS ALREADY PRESENT (PERHAPS UNDERTHRUST FAULT FROM EAST). SEDIMENTATION STARTING.



2. NEAR END OF ALGONKIAN TIME (OR PERHAPS EARLY CAMBRIAN TIME). ALGONKIAN GEOSYNCLINE COMPLETED.



3. UPPER CAMBRIAN TIME. RELEASE OF STRESS. RISE OF APPALACHIA.

FIG. 4

force. Gunn himself explains the presence of the stress by a variant of the continental drift theory which involves the density difference between continental and oceanic regions (Gunn, 1936). However, the results of this paper would be the same for any other theory from which the proper value of compressive stress is derivable.

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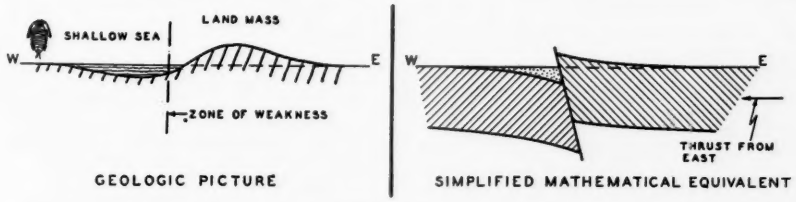
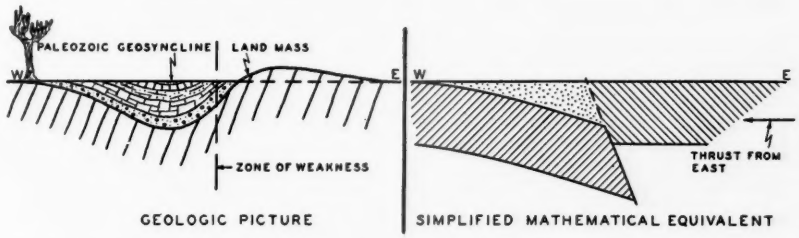
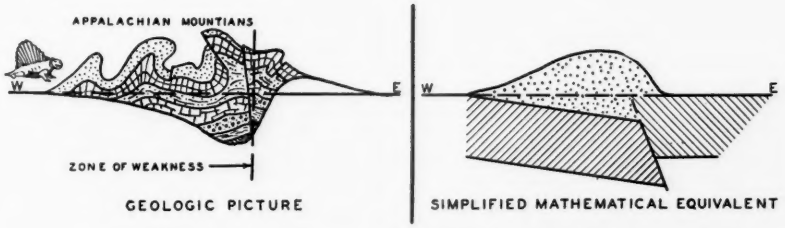


4. LATER IN UPPER CAMBRIAN TIME. LAND ON EAST, SEA ON WEST. RENEWED STRESS (PERHAPS OVERTHRUST) FROM EAST. SEDIMENTATION STARTING.



5. PENNSYLVANIAN TIME. PALEOZOIC GEOSYNCLINE COMPLETED.



6. PERMIAN TIME. APPALACHIAN REVOLUTION. RELEASE OF STRESS (PERHAPS ONLY PARTIAL) WITH ISOSTATIC RISE, FOLLOWED BY FOLDING AND FAULTING CAUSED BY RENEWED THRUST FROM EAST; THE FORMATION OF THE MAJOR APPALACHIAN MOUNTAINS.

FIG. 4. Hypothetical history of the Appalachian Mountains.

Paul D. Foote and Dr. E. A. Eckhardt, for permission to publish this paper.

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A MECHANICAL DEVICE FOR COMPUTING SEISMIC PATHS*

ALEXANDER WOLF†

ABSTRACT

The paper describes a mechanical device for the computation of the circular seismic paths occurring in a medium in which the velocity increases uniformly in one direction.

A common practice in seismic exploration is to approximate the actual variation of velocity with depth by a function of the form

$$v_y = v_0 + ay, \tag{1}$$

where v_y is the velocity at depth y, v_0 is the velocity at the surface ($y=0$), y is the depth, and a is a constant. It is well known[1] that if the velocity varies in accordance with expression (1) both the paths of the waves and the wave fronts are circles. The centers of the wave fronts lie on a vertical through the point at which the wave started (shot point), while the centers of all wave path circles lie on a horizontal line a distance $K=v_0/a$ above the surface of the ground (line of zero velocity). The transit time between any two points 1 and 2 can be written in the form

$$t = \frac{1}{a}\left[ln \tan \phi_2/2 - ln \tan \phi_1/2\right],$$

where ϕ_1 and ϕ_2 are the angles at which the wave paths are inclined to the vertical at the two points 1 and 2 respectively.

Since both wave-fronts and paths are circles, and time can be measured in terms of a simple function of two angles, it would appear to be very simple to construct a mechanical device which would give any parameter in terms of the others. The difficulty encountered in practice lies in the great length of the radii of curvature of some of the wave paths. This either restricts the application of the machine to paths of small radius of curvature (shallow penetration), or makes the dimensions of the machine prohibitively large.

A solution of the problem lies in a suitable distortion of the coordinates. Peterson[2] has shown how this can be accomplished. Briefly, if a conformal transformation

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† The Texas Co., Houston, Texas.

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[2] GEOPHYSICS, VI, pp. 74–80, 1941.

$$W = p + iq = i_2Rz/(z + i_2K), \tag{2}$$

where

$$z = x + iy, \tag{3}$$

is applied to the conventional representation of wave path and wave front (Fig. 1), then in the W-plane (coordinates p and q) one obtains the transformed diagram of Fig. 2, in which all wave paths are straight lines through O, all wave fronts are circles concentric on O, and hori-

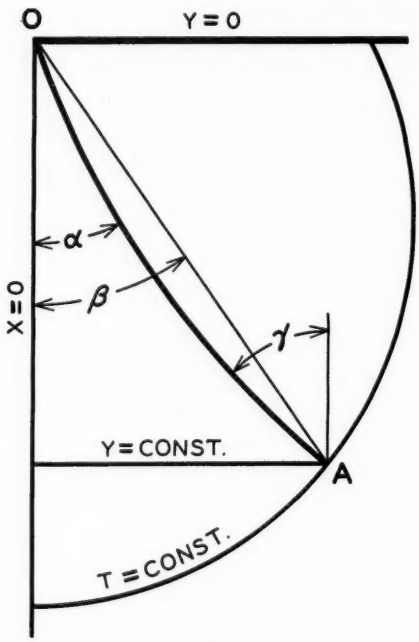

FIG. 1. Wave path and wave front in Cartesian coordinates.

zontal lines (y=const.) become circles through O', with centers on line OO'. In particular, the surface of the ground (y=0) becomes a circle of radius R, so that the entire subsurface is included within a finite space in the transformed diagram. Since the transformation is conformal, angles α and γ of Fig. 2 are the same as the corresponding angles in Fig. 1. Vertical lines (x=const.) of the undistorted diagram become circles after transformation. All these circles run through O', and their centers lie on a horizontal through O'. The radii of cur-

vature of these circles are very large for small x, so that it is not practical to construct these circles. It becomes necessary to employ a different parameter to locate such a point as A (Fig. 1 and Fig. 2).

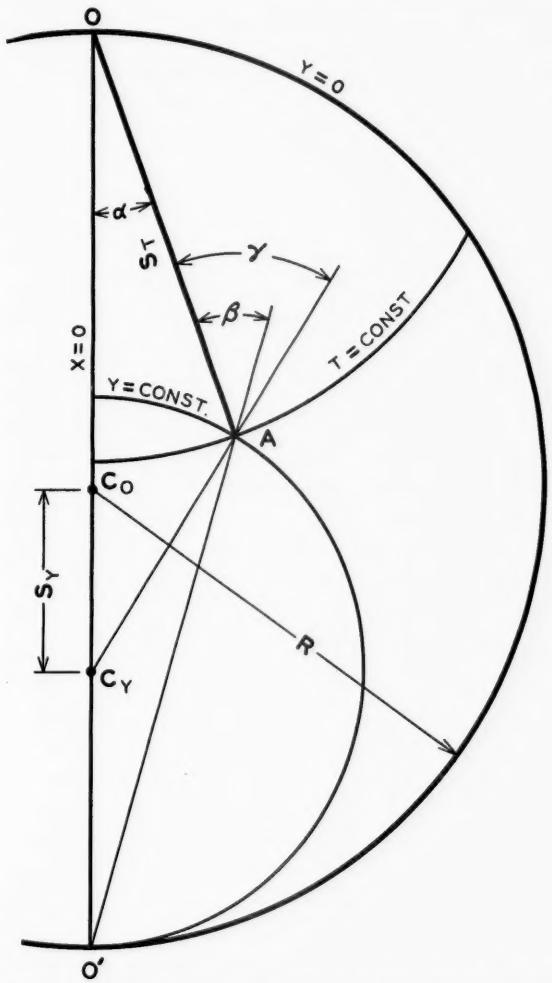

FIG. 2. Wave path and wave front in transformed coordinates.

Referring to Fig. 1, we note that point A can be located by means of the parameters γ and β, where β is the angle between the vertical and the radius vector from O to A. Simple geometrical considerations lead to the result

$$\beta = \tfrac{1}{2}(\alpha + \gamma). \tag{4}$$

In Fig. 2 it is also found by simple geometry that the acute angle between OA and AO' is equal to $\frac{1}{2}(\alpha+\gamma)$. Hence angle $OAO'=\beta$, as indicated in Fig. 2.

The construction of the computing device follows immediately from a consideration of Fig. 2. A schematic diagram of the device is shown in Fig. 3. A bar OO' (Fig. 3) carries pivots at O and O', which correspond to O and O' of Fig. 2. A straight arm OA pivoted at O obviously represents a wave path. The angle between arm OA and bar OO', read on a divided circle attached to bar OO', is the angle of emergence α. Since in Fig. 2 the wave-fronts are concentric on O, a suitable time scale can be attached to arm OA, and a slide running on this arm can be set to any travel-time by means of that scale. Slide A carries a divided circle and a pivot on which is mounted a rod AO'. The latter slides freely in pivot O', as shown in Fig. 3. A pointer attached to rod AO' reads the angle β on the divided circle attached to slide A. All that remains is to determine angle γ and the depth y. Reference to Fig. 2 will show that this can be accomplished if we establish mechanically the center C_y of the constant depth circle through A. Obviously the position of C_y along bar OO' depends only on the depth of point A, so that a scale of depth (y) can be attached to bar OO'. The position of slide C_y along this bar will then read depth of A on the latter scale. To establish C_y we note in Fig. 2 that C_y is equidistant from A and O', regardless of the position of A. We now pivot arm AC_y at A. The other end of this arm carries a gear rack (Fig. 3) which engages a small gear supported on slide C_y. This gear in turn engages a gear rack attached to bar OO'. An examination of Fig. 3 will show that once slide C_y is set in the correct position on bar OO', it will always remain equidistant from A and O', because of the interaction of the two gear racks through the medium of the circular gear. Therefore, once it is properly set, the slide C_y will automatically place itself at point C_y of Fig. 2. We also note that a pointer attached to arm AC_y reads angle γ on the divided circle attached to slide A. In conventional operation of the device, if travel-time from origin and angle of emergence of a wave are known, slide A is moved to the correct position along the time-scale, arm OA is rotated to the correct angle α, and then angles β and γ, and the depth y are read directly from the scales.

In the construction of an actual instrument one additional refinement is required. The schematic gear mechanism of Fig. 2 will operate

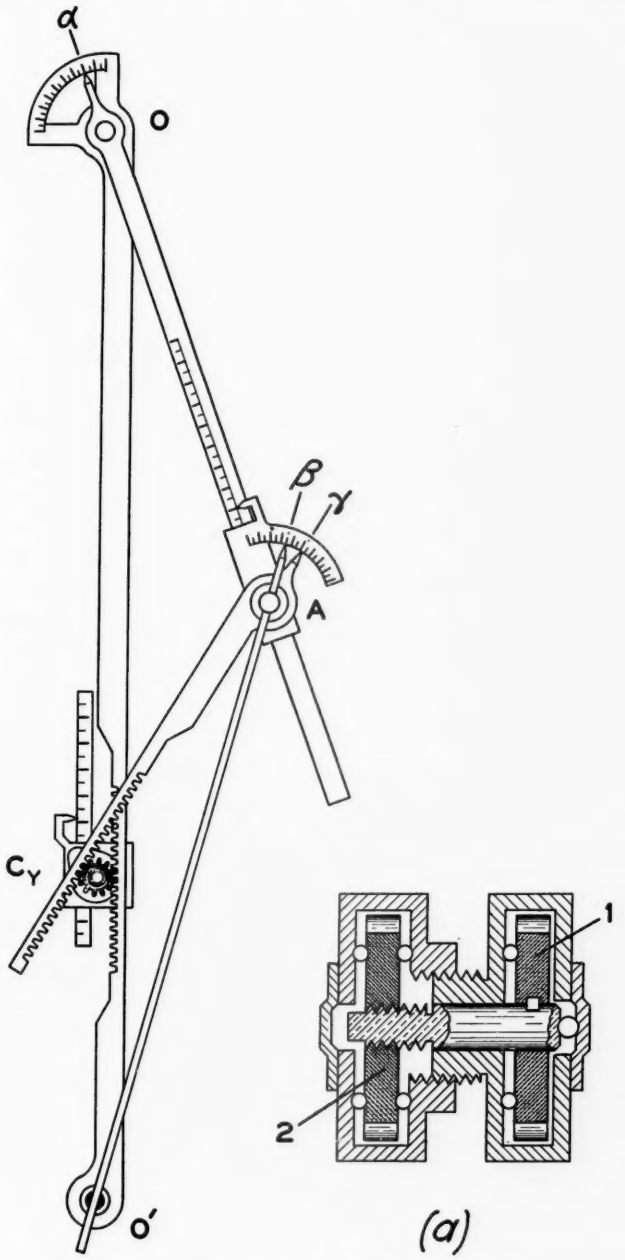

FIG. 3. Schematic diagram of computing device.

correctly only if the circular gear is infinitesimally small. In reality the gear must be of finite size. Reference to Fig. 3 will show that a translation of the pivot at A in the direction C_y will result in a motion of slide C_y along OO' of the correct magnitude. On the other hand a pure rotation of pivot at A around C_y should not move C_y. Actually, however, although the rack on arm AC_y will not slide relative to the pivot at C_y, the rack will rotate around pivot C_y and will carry the circular gear with it. The latter in turn will cause motion of the slide C_y along OO'. To remedy this defect the circular gear is replaced by two identical gears on the same shaft, as shown at (*a*) in Fig. 3. Each gear engages only one rack. Gear *1* is firmly attached to the shaft, while gear *2* is keyed to a helical groove in the shaft. The distance between the two gears is controlled by their housings, which are also keyed together by means of a helical groove of the same pitch as the helical groove on the shaft. Arm AC_y passes through the housing of gear *2*, which is consequently always aligned with this arm. With this construction a pure rotation of arm AC_y around C_y results in a rotation of housing *2*, which in turn changes the separation of the two housings. Gear *2* revolves along the helix cut in the shaft without rotating the shaft, and, hence, without displacing slide C_y from its correct position. A sliding motion of the rack, on the other hand, does not change the separation of the gear housings, so that gear *1* drives the shaft and gear *2*, resulting in the proper displacement of slide C_y.

Fig. 4 is a photograph of a completed instrument in which the distance between pivots O and O' was made 40 inches. The divided circles are standard metal protractors. The time and depth scales are not linear, and depend on the parameters v_0 and a of the velocity function (1). It was found that for ordinary velocity functions and an instrument in which $OO'=40''$ ($R=20''$) the scales are amply large for seismic reflection work.

The calculation of the depth and time scales is effected as follows: As mentioned already, point C_y (Fig. 2) is the pointer on the depth scale. When $y=0$ (surface of ground), point C_y is at C_0, the center of the circle $y=0$, a distance R below the origin O. Therefore the zero of the y-scale is half-way between O and O'. We now consider the transformation of the vertical through the origin $z=iy$. Substituting in (2):

$$W = p + iq = i2Ry/(y + 2K)$$

$$q = 2Ry/(y + 2K). \tag{5}$$

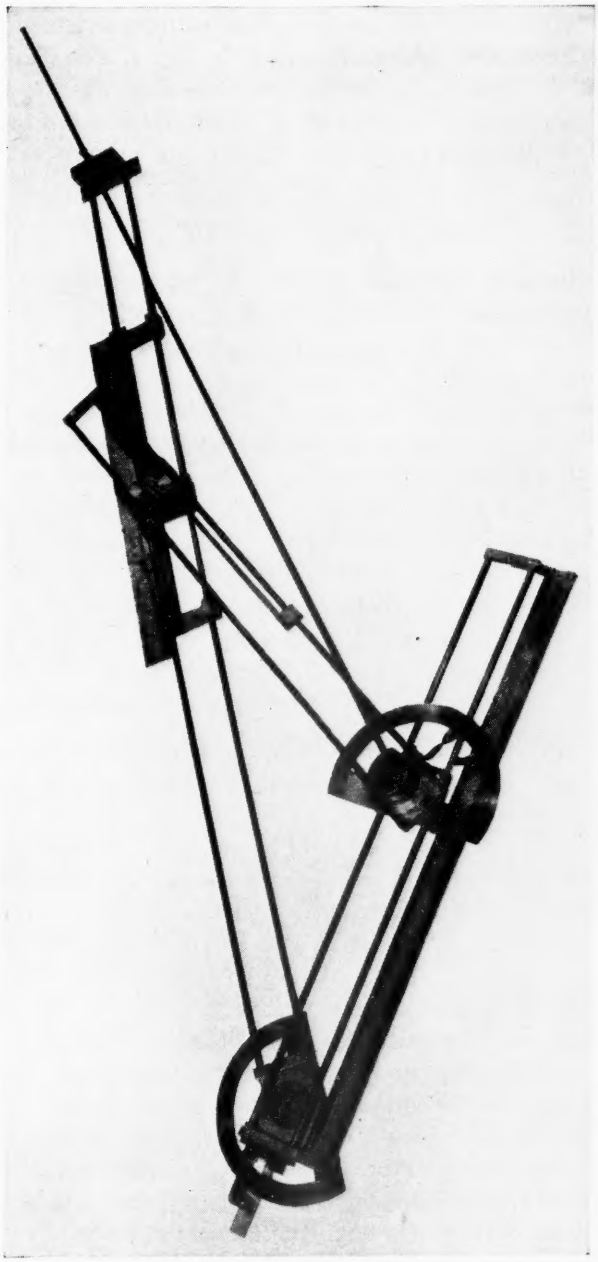

FIG. 4. Mechanical computing device.

Expression (5) gives the distance from O to the intersection of the circle $y=$const. with the vertical through O in Fig. 2. The diameter of this circle is obviously $2R\text{-}q$, and the radius is $R\text{-}q/2$. Hence the distance S_y of Fig. 2 is $q/2$. Note that S_y is the displacement of the depth pointer C_y from its zero C_0 corresponding to depth y, i.e., S_y is the new depth scale.

$$S_y = q/2 = Ry/(y + 2K). \tag{6}$$

It is interesting to note that the depth scale depends only on the size of the instrument (R), and on the ratio $K=v_0/a$. For instance, if $K=15{,}000$ ft., and $R=20''$, $S_{1000}=0.645''$. A scale of this size can be easily read to the nearest 50 ft.

The time scale is placed on arm OA. O is the zero of the scale, and A is the pointer. We consider the depth along the vertical which the wave reaches in time t:

$$t = \int_0^y dy/(v_0 + ay) = \frac{1}{a} ln(1 + ay/v_0)$$

$$y = v_0(e^{at} - 1)/a. \tag{7}$$

Substituting in (6):

$$q = 2R(e^{at} - 1)/(e^{at} + 1) = S_t \tag{8}$$

where S_t is obviously the time-scale. We note that the time-scale depends only on R and a, but not on v_0. For instance, if $R=20''$, and $a=0.4$ sec^{-1}, then for $t=0.5$ sec., $S_{0.5}=3.98''$. In reflection work the point $3.98''$ from O on arm OA would be marked 1.0 sec., rather than 0.5 sec., since back and forth travel-times are usually measured.

The construction of an instrument such as shown in Fig. 4 requires expert workmanship, if back-lash is to be eliminated and the parts are still to move freely. The construction is not justified unless the instrument is to be used quite extensively. Once the instrument is available, however, the calculation and drawing of the special time and depth scales requires no more than about two hours. The instrument is quicker and incomparably less tiresome to use than the variety of charts with which the same object is sometimes achieved. Obviously, where the curvature of the path can be neglected, as in the computation of small dips, or where certain approximations are permissible, the use of the instrument is totally out of place.

A STUDY OF ELECTRICAL EARTH NOISE*

E. F. NEUENSCHWANDER† AND D. F. METCALF†

ABSTRACT

A method of investigation into the characteristics of electrical ground noise is described. The factors involved in the origin and distribution of ground static and the value of noise level surveys as applied to geophysical prospecting are also given.

The evidence accumulated during this study, both qualitative and quantitative, indicates fairly conclusively that earth static has, for the most part, the same origin as atmospheric static. It is possible, of course, that a portion of ground static originates within the earth, but the relative contribution from such sources is believed to be small.

There are several possible causes of electrical noise within the earth. In the first place, there might be a phenomenon in the earth similar to that responsible for atmospheric static. It is generally conceded that atmospheric static is principally a result of excessive turbulence of dust-laden or moisture-laden air, such as occurs during the formation of fog, thunderclouds, and dust storms. It is difficult to conceive of a convection process within the earth by which its electrical condition could be disturbed sufficiently to generate static of the intensity encountered.

Other conceivable internal sources of earth static can be mentioned. Thus, the natural earth current might produce electrical noise in crossing a geologic contact, for example. Electrochemical action of some kind could possibly generate electrical disturbance having the character of static. Thermal agitation is another interesting possibility. Also, the shifting of sand might cause static. In consideration of the fact, however, that hourly variations in terrestrial static level closely follow the hourly variations in atmospheric static level, it is believed that the predominating portion of the former has the same origin as the latter.

APPARATUS AND MEASURING TECHNIQUE

The measuring technique developed in this investigation for studying the distribution of earth static utilized a comparative

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† Geophysics Research Division, Humble Oil & Refining Co., Houston, Texas.

method. Absolute methods were found to be of little value owing to the erratic nature of earth static. Such measurements, moreover, must be corrected for the diurnal and secular variations in absolute noise level which occur more or less uniformly over an entire region as a whole. Relative measurements, on the other hand, are unaffected by any such time variations and in addition are capable of much higher observational accuracy.

Fig. 1 shows a block diagram of the equipment. The noise waveforms picked up from electrodes *ab* and *cb* were fed into the compensating networks *CC*, then into each triode section of the mixer, and an adjustment of the two attenuators *AA* for a null balance as indicated

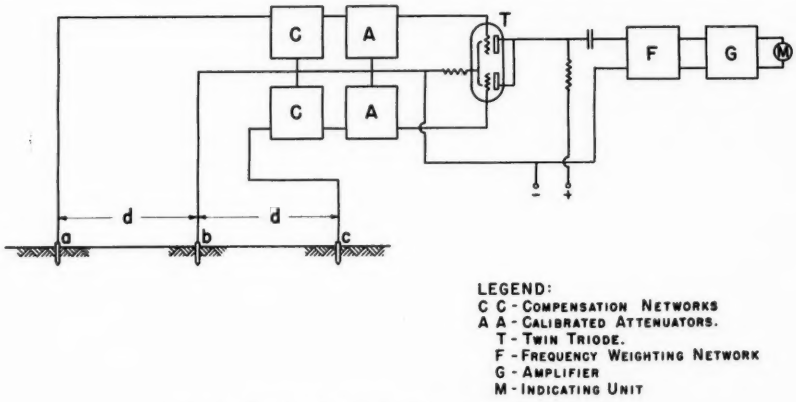


FIG. 1. Functional diagram of measuring apparatus.

by the output meter *M*. The compensating network *CC* inserted in each signal channel automatically corrected the results for variations in contact resistance at the electrodes. Shunt condensers were placed across each attenuator input to bypass radio frequency currents due to local broadcasting stations which would otherwise find a way into the balancing circuit to be demodulated and would be passed on to the indicating unit. The frequency weighting network comprised a high pass filter and a band pass filter. By the use of a high pass filter cutting off around 250 cycles/sec., measurements within a few hundred feet of high voltage power lines were possible. A switching arrangement was used in conjunction with the band pass filter to set the mean pass frequency at nominally 0.4, 1, 3, 5, 7, 9, 11, 13, and 15 kc./sec. The amplifier *G* comprised four untuned amplifying stages, providing a usable gain in excess of 110 db.

The experimental procedure in all cases consisted simply in an adjustment of the two attenuators *AA* for a null balance, as indicated by the output meter *M*, after first adjusting the compensating network *CC*. At this point, the ratio of the fractional attenuation required in each channel for balance is numerically equal to the desired ratio of the two noise waveform amplitudes, provided the voltage gains of the two triode sections are equal. In determining the noise level profile along a given traverse, the entire equipment was moved along the

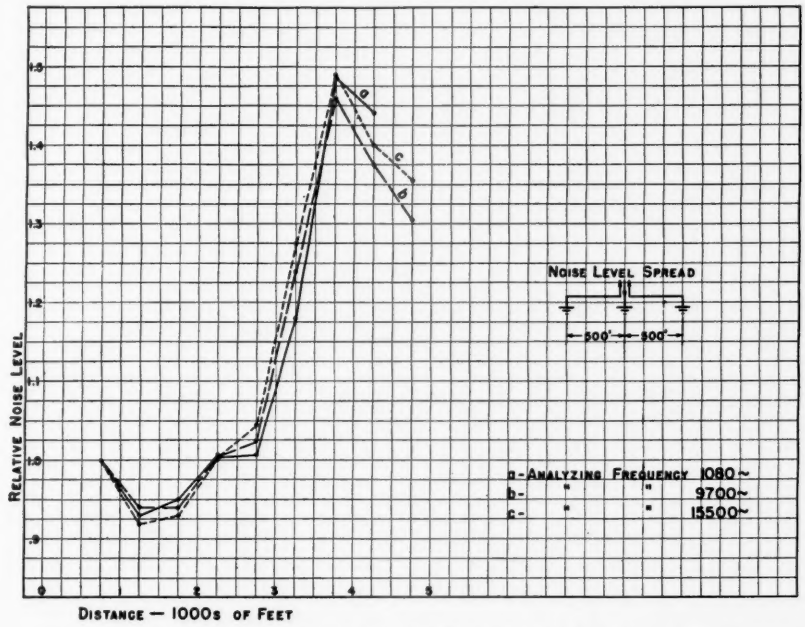


FIG. 2. Variation in noise level with analyzing frequency.

traverse in equal steps, the measuring procedure being repeated at each station. The distance moved at each step was kept equal to the electrode spread *d*, thus making it possible to determine the noise level corresponding to any given location in terms of the level at any other specified location simply by multiplying together all the measured ratios between the two locations in question. All profile data referred to in this report were obtained in this fashion, the mean analyzing frequency in all cases being approximately 10 kc./sec., with an effective bandwidth of about 2 kc., except where otherwise indicated.

Profiles obtained, using each of the above mentioned frequencies,

provided data for studying the dependence of static distribution on the analyzing frequency. It was found in several areas that profiles thus obtained with analyzing frequencies from 1 to 15 kc. were not significantly different as shown in Fig. 2. Unfortunately, measurements below about 1000 c.p.s. proved to be unreliable. It appears that the portion of ground static below this frequency consists principally of isolated impulses of random amplitude and as such is not amenable

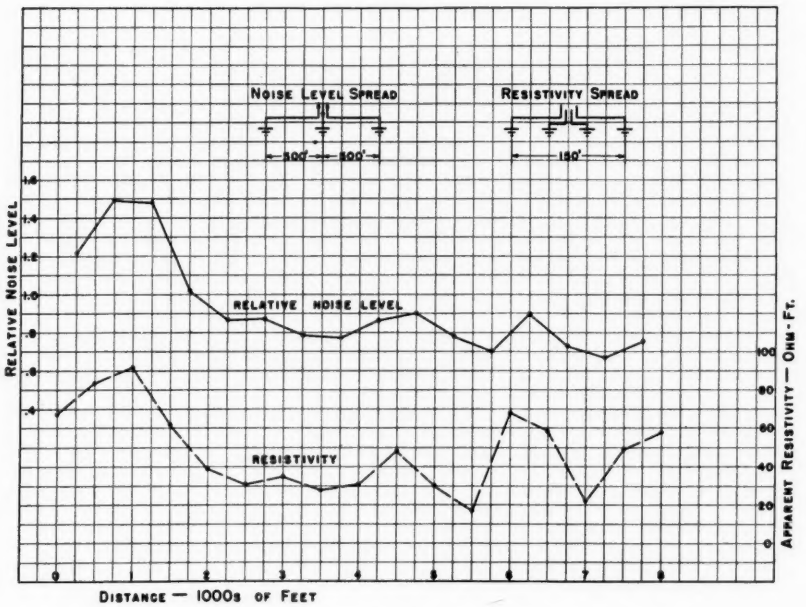


Fig. 3. Relative noise level *vs.* resistivity in the Blue Ridge area.

to accurate measurement. The portion above 1000 c.p.s., however, has characteristics strongly resembling tube hiss and thermal agitation noise in conductors, and as such is amenable to quite accurate measurement.

The noise waveforms picked up from electrodes *ab* and *cb* were found in practically all cases to be substantially identical, as long as the three electrodes were in a line, as would be expected. An interesting sidelight in this connection is the dependence of the frequency characteristic of earth static as picked up from a single pair of electrodes at a given location upon the orientation of the line of electrodes.

In one case, in the Stratton Ridge* area, it was found that the absolute noise level measured, using a filter tuned to around 9000 c.p.s., more than doubled as the electrode line was rotated from the northeast to northwest. The noise level measured with a 13 kc. filter, on the other hand, showed a minimum at approximately due north as the electrode line was rotated. It was further noted that in some instances only a broad balance was obtainable with the comparative method when the

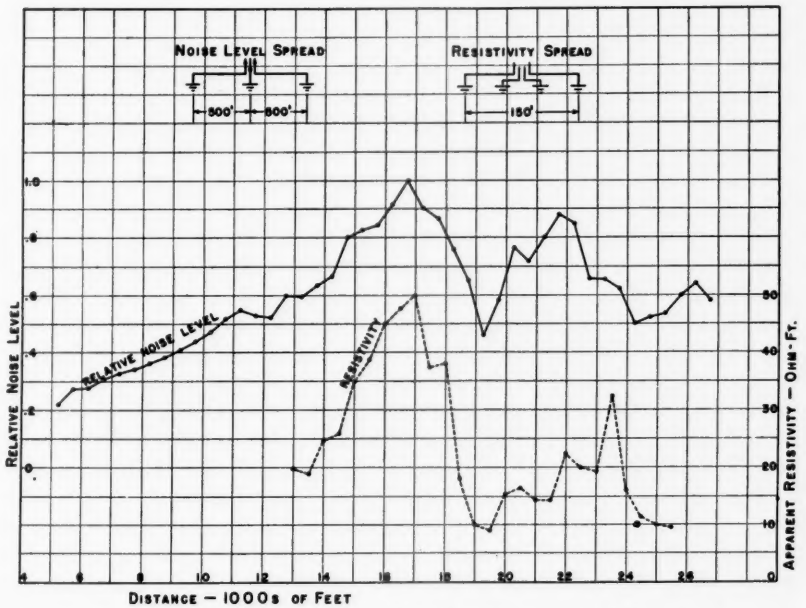


FIG. 4. Relative noise level *vs.* resistivity in the Stratton Ridge area.

front and rear lines of electrodes were not in line, the balance becoming increasingly broader as the two lines departed farther from collinearity.

RESULTS

Before attempting to ascertain the effect of geological and geophysical variations on noise distribution, it was felt necessary to determine first whether or not there existed any diurnal or secular variations in the distribution profiles, even when measured by a relative method.

It was found rather quickly that no hourly variations existed, sim-

* Near Houston, Texas.

ply by taking a series of semi-hourly noise level measurements at a few fixed locations. During one day's run, in fact, a thunderstorm formed overhead and moved southward. No change in the noise level ratio was observed while this happened. To determine the extent of secular variations, a profile in the Blue Ridge* area was run completely several times during the entire investigation. No significant difference in any of these profiles was observed.

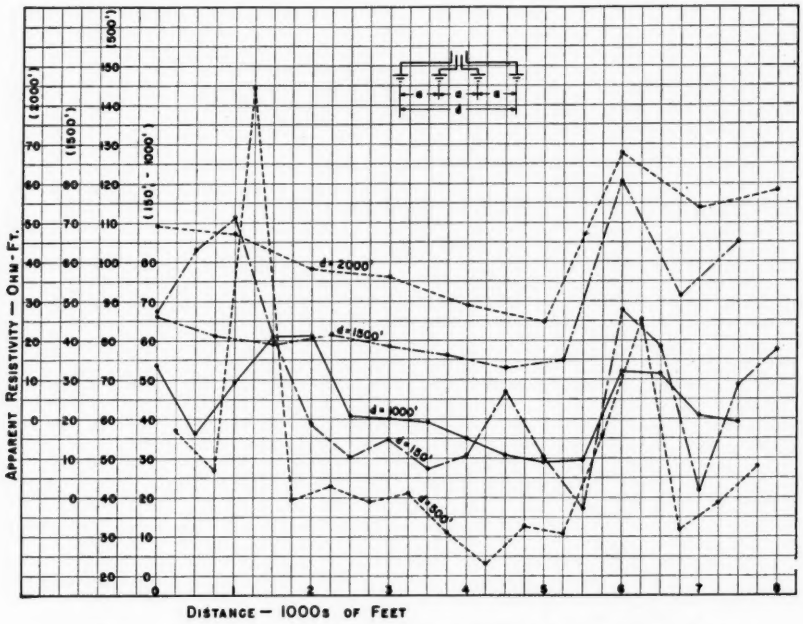


FIG. 5. Variation in d.c. resistivity with change in current spread.

Attention was then directed to the question of the effect of geological and geophysical variations on static distribution. As was expected, shallow variations in earth resistivity (for the sake of brevity, "resistivity" is used to mean apparent resistivity) along a traverse were found to coincide closely with variations in noise level, as shown in Figs. 3 and 4. In fact, a close enough correspondence between shallow resistivity and noise level was found in enough different cases to justify the conclusion that shallow resistivity is usually the principal factor determining the noise level distribution in a given area. The resistivity profiles shown were obtained using direct current and a

* Near Houston, Texas.

Wenner electrode configuration having a current spread of 150 feet. Other factors apparently are affecting the noise level profile, but these are probably unimportant except possibly in an area where the shallow resistivity is fairly uniform.

For the purpose of obtaining somewhat more exact information regarding the influence of shallow resistivity, a series of d.c. resistivity profiles was obtained as shown in Fig. 5. The Wenner configuration

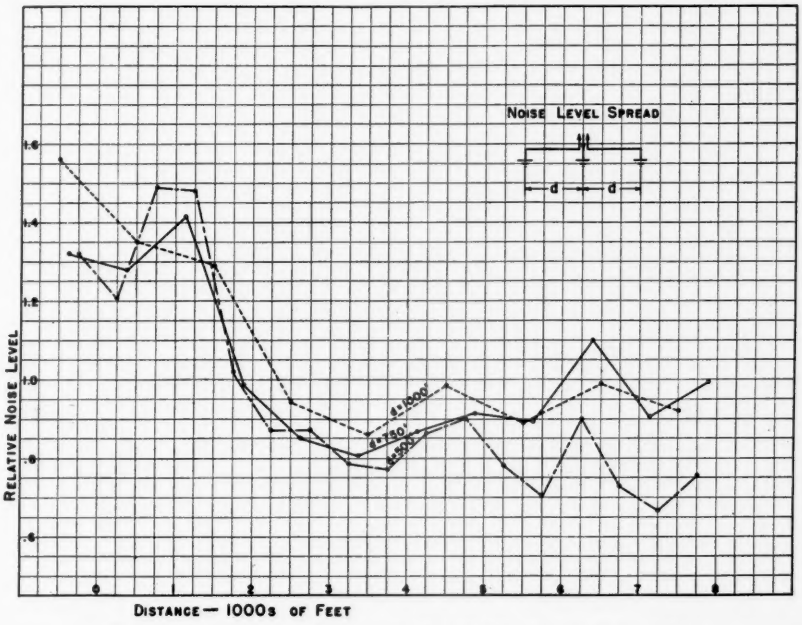


FIG. 6. Variation in relative noise level with change in spread.

was used as before, and current spreads of 500, 1000, 1500, and 2000 feet employed. A series of noise level profiles was obtained with electrode spreads of 750 and 1000 feet as shown in Fig. 6. It is evident upon inspection of the two groups that the correlation between noise level and resistivity does not exist for the longer resistivity spreads. A notable feature of the curves of Fig. 6 is that the character of the noise level profile is not greatly affected by the spread used.

It has been suggested that natural earth current is connected in some way with noise level distribution. To investigate this possibility, several locations in the Blue Ridge area were repeated with a d.c. ground-return circuit laid out parallel to and of the same length as one

of the noise level lines. The minimum allowable separation between lines was determined from a preliminary experiment in which it was found that the electrical noise originating at the current electrodes themselves for currents of 10 amperes or less produces a negligible effect in the noise level circuit as long as the two lines were separated by 10 feet or more. It was then found that with current values ranging from 1 to 10 amperes, no change in the noise level ratio could be detected. Assuming that an artificial earth current has essentially the same effect on the local noise level as the natural earth current, it appears, then, that natural earth current is not a contributing factor in determining the noise level distribution.

APPLICATION TO GEOPHYSICAL PROSPECTING

It was stated above that, in view of the evidence shown, the shallow resistivity is usually the principal factor determining the noise level distribution in a given area. Ground noise measurements thus afford another method of determining the variation in shallow resistivity over an area. Inasmuch as this resistivity is the predominating influence, however, there seems to be little prospect of employing noise level measurements to indicate other electrical quantities.

Moreover, the use of noise level measurements in determining the variations in shallow resistivity does not appear to possess unique advantages over existing methods, either from a standpoint of increased accuracy of data or of facilitated field procedure. No estimates of accuracy are available owing to the absence of any sort of standard, but the margin of error is not believed to be larger than $\pm 5\%$.

In regard to field procedure, the noise level method requires a total wire spread of around 1000 feet to obtain data essentially equivalent to d.c. resistivity data obtained with a current sprread of only 150 feet. In addition, noise level measurements are in some locations unreliable, due to such factors as disturbance from power lines, excessive broadness of balance, and others. Finally, accurate noise level measurements necessitate a relative method of measurement, as pointed out above, and relative geophysical methods are disadvantageous for several familiar reasons.

Some light can be thrown on the question of effective penetration of this method by consideration of Figs. 3 and 5. In these figures, it will be seen that the noise level profile coincides most closely with the 150 foot resistivity profile. Similar data on other lines point to the same conclusion. Apparently, these noise level profiles are not greatly

influenced by resistivity variations below about two or three hundred feet. Furthermore, this penetration is not increased even with analyzing frequencies as low as 1000 c.p.s. according to Fig. 2. It would appear, then, that the penetration obtained by this method is predetermined by the electrical earth characteristics in the area in question, and not by the particular frequency or electrode spread chosen. This is not surprising, of course, and is characteristic of methods measuring natural geophysical quantities, as for example, the gravitational and magnetic methods. This is supported by the results of Fig. 6 where it is seen that an increase in electrode spread has little effect on the character of the profile obtained.

We are consequently led to the conclusion that, under most circumstances, the noise level variations along a traverse correpsond closely to variations in the shallow d.c. resistivity along this traverse such as measured with a current spread of around 150 feet. In other words, earth resistivity variations below two or three hundred feet usually have only a small influence on the noise level distribution measured at the surface. The prospect of increasing this penetration by recourse to lower analyzing frequencies is not encouraging, for reasons mentioned above.

REFLECTED REFRACTIONS*

C. A. SWARTZ† AND R. W. LINDSEY†

ABSTRACT

A number of very steep reflections were observed while making a seismograph survey of a salt dome. A time plot of events recorded along a typical profile is shown. The steep reflections came both from the sides of the dome material and from the adjacent upturned sedimentary strata. A particular event of very infrequent occurrence, a reflection from the vertical side of the dome traveling essentially horizontally along a refracted trajectory, is discussed in detail.

In the course of a recent seismograph survey of a salt dome in Louisiana a large number of very steep reflections were observed. Some of them were of particular interest to the authors because, in their experience with seismograph records, they had never before noticed such clear-cut examples of reflections with step-out times so large that their interpretation required a wave traveling in a practically horizontal direction, reflected from a very nearly vertical interface. Although such events have no doubt been observed by others, they are believed to be unusual enough to warrant a brief description.

Fig. 1 is a time plot of reflections obtained along a portion of one of the profiles of the survey which clearly exhibits several very steep reflections. The shot points were laid out in a straight line directed more or less radially with respect to the dome. Practically continuous control was provided. With 50 foot spacing, the detectors covered the distance between successive shot points which furnished shots from both directions to each set-up. The observed reflection times, corrected to sea level, were plotted on the horizontal scale midway between the corresponding shot point and detector. For clarity in the figure, the reflection time at every other detector position was omitted. The first arrival times of the refracted energy were plotted at their respective detector positions.

It will be noted that most of the plotted events represent reflections from horizontal sub-surface beds. There are also, however, several steep reflections which are evidently coming either from the sharply upturned sedimentary strata adjacent to the dome or from the flank of the salt plug itself. The horizontal reflections interfere with the steep ones when their arrival times coincide, thus tending to

* Presented at the Annual Meeting, Houston, Texas, April 2, 1941.

† Gulf Research & Development Co., Pittsburgh, Pa.

obscure both events. However, reflections "*A*," "*B*" and "*C*" are clear enough to be susceptible of fairly accurate measurement.

All reflection paths, including those from horizontal beds, of course, undergo a certain amount of refraction due to variation of the

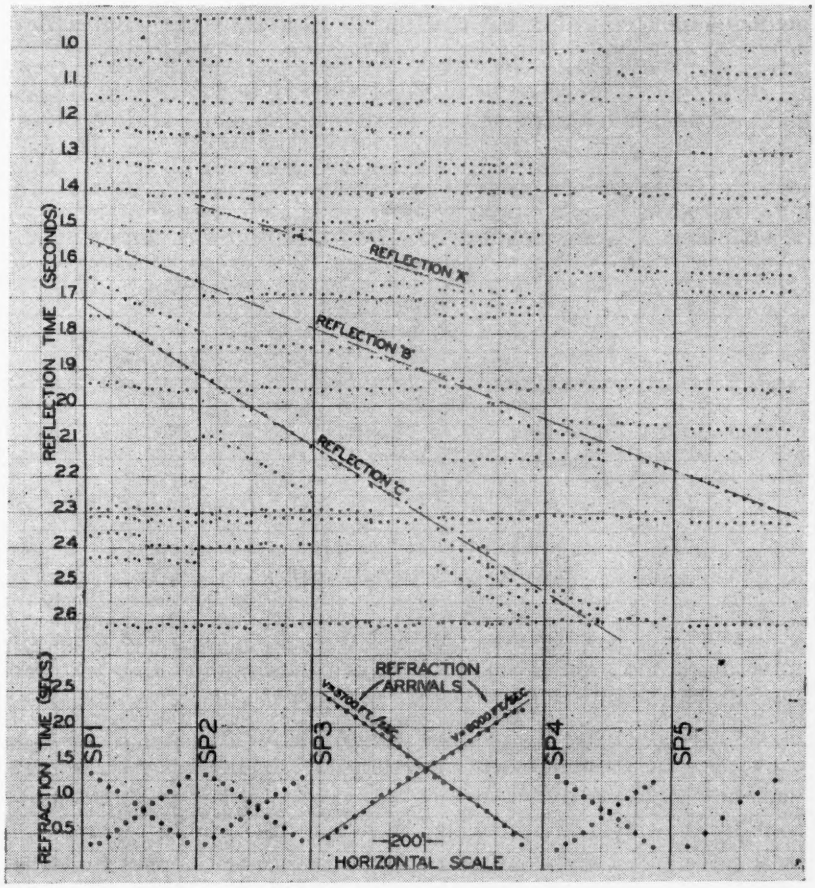


FIG. 1. Reflection and refraction arrival times plotted along a profile radial to a salt dome showing, in particular, reflections "*A*," "*B*" and "*C*" from very steep surfaces.

velocity of the sediments with depth. Moreover, as the reflecting interface departs from the horizontal and becomes steeper and steeper the reflection trajectories suffer more and more refraction because of their increasing horizontal component of travel. Thus, reflections

"*A*" and "*B*" which are from interfaces dipping rather steeply, at angles of the order of 45°, must have been bent considerably by refraction in traveling along their paths. Finally, in the extreme case where the reflecting surface is vertical, the refracting effect of the traversed sediments, as determined by the velocity variations therein, is the predominant factor affecting the course of the trajectory. Reflection "*C*" is an example of a refracted reflection of this extreme type.

Reflection "*C*" was recorded persistently from shot points 1, 2, 3 and 4 at times ranging from 1.7 to 2.6 seconds. Its step-out time, being

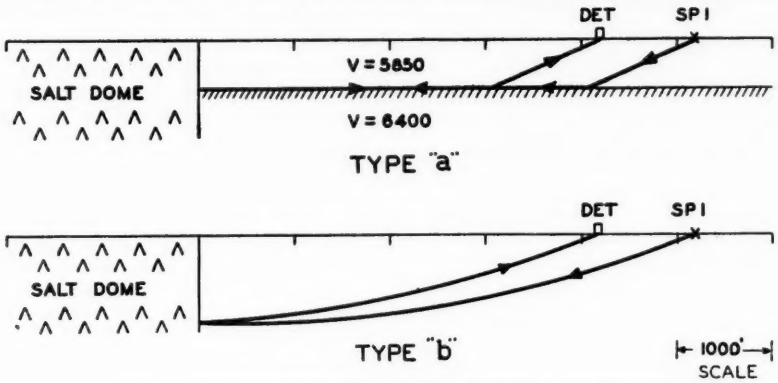


FIG. 2. Diagrams showing two possible types of trajectories traversed by reflection "*C*" of Fig. 1.

a measure of the horizontal component of velocity of the reflected wave along the profile, shows that this component is 6400 feet per second. This is only slightly greater than the velocity of propagation in the consolidated stratum just below the surface zone, which is shown by the refraction first arrivals to be 5850 feet per second. It may be concluded that the reflected wave is either traveling horizontally in a single refracting bed whose speed is 6400 feet per second, or is traveling in slightly slower speed material and approaching the surface at a small angle. Fig. 2 is a diagram illustrating schematically the two possibilities. If the actual path is of type "*a*" the step-out time measures directly the velocity of propagation in the refracting bed. If it is of type "*b*," the step-out time measures the velocity in the near-surface sediments divided by the cosine of the small angle at which the wave path approaches the surface.

The shortest distance from shot point 1 to the dome, whose cap rock outcrops on the surface, is known to be close to one mile. The

maximum penetration of a trajectory of type "*b*," calculated on the basis of a linear rate of increase of velocity known to be reasonable for this area, would be about 1000 feet. For a trajectory of type "*a*" the refracting bed of velocity 6400 feet per second can be only a few hundred feet below the surface. In either case the path is essentially horizontal over most of its length. Also, the observed times are compatible with the calculated total travel times to and from the dome over either trajectory, so there is little doubt that one of them represents the true travel path.

THE EFFECT OF MUD RESISTIVITIES ON THE INTENSITIES OF ELECTRICAL LOGS*

M. C. BOWSKY†

ABSTRACT

The drilling mud is one of the variables that prevents comparing the actual intensities of electrical logs. This paper deals with the effect of the resistivity of the drilling mud on the intensities of the natural potential and normal apparent resistivity curves.

In the Gulf Coast, standardized well conditions are seldom available. There are occasions when there is even no similarity between two electrical logs in the same field when one well is logged in extremely low resistivity drilling mud and the other in comparatively high resistivity mud. If the resistivity of the drilling mud had been high in both cases, however, the electrical logs could have been readily correlated. Therefore, in order to even compare electrical logs of adjoining bore holes, the well variables must be considered.

The results of a series of tests to determine the effect of the well variables on electrical logs indicated that variations in the resistivities of the drilling mud caused the greatest change on the electrical measurements. This is logical as the bore hole diameters, in general, do not vary to any great extent and in most cases—barring unforeseen troubles—the drilling time is approximately the same. The resistivity of the drilling mud, however, can and does vary over a large range. In some bore holes, the mud may become contaminated with salt water from drilling through or into the salt, or by a salt water flow into the hole. In one well in particular, on successive runs, the drilling mud resistivity changed from 15 ohm-meter at 82°F. to 0.05 ohm-meter at 82°F. During the first run, fresh water mud was used while on the second run, the drilling mud resistivity was lowered by drilling into the salt.

Acknowledging the importance of drilling mud resistivities on electrical logs, a series of tests were then made to determine if the resistivity of the drilling mud sample when measured at the well by the operators of the electrical logging equipment is indicative of the true resistivity of the drilling mud in the bore hole at the time of logging. Such mud resistivity measurements are made when the equipment

* Presented at the Annual Meeting, Houston, April 2, 1941.

† Lane-Wells Company, Houston, Texas.

reaches the well and it is usually after circulation has stopped. The mud samples are generally taken from the mud pit, and it is quite possible that this mud could have been diluted; for example, by rain, by the addition of fresh water while washing off the rig floor, or contaminated by some chemical and, consequently, the resistivity of the mud sample would not necessarily denote the actual resistivity of the drilling mud in the bore hole at the time of logging.

In order to determine the correct resistivity of the drilling mud, the drilling crews were instructed to take special one quart samples of the mud coming out of the bore hole fifteen, ten and five minutes before circulation had stopped, and just prior to pulling pipe for the logging run. They were also informed, the samples would not be acceptable unless the fluid had been thoroughly circulated after the addition of any other materials. For comparison the mud resistivity was also tested in the normal manner by the logging operators when they reached the well.

When the normal and special samples were compared, it was found that two of the samples checked very closely and, therefore, the normal samples evidently indicated approximately the true resistivity of the mud in the bore hole at the time of logging. Three of the samples did not coincide. The special samples were of a lower resistivity, which is a condition which might be expected, and they were probably more indicative of the actual resistivity of the fluid in the well at the time of the logging. The remaining two samples again did not coincide but they were of a higher resistivity than the normal samples. This was unexpected, but the special samples may have been taken, in spite of instructions, after the addition of fresh water in the drilling mud and before sufficient time had been allowed for adequate circulation. It is conceivable, however, that even though the last two special samples were higher, they could have indicated the true resistivity of the mud in the drill hole as the normal samples could have been taken from a place where the mud was never in circulation or was contaminated.

In order to be certain of the mud in the bore hole, the drilling mud samples for all the following tests were taken during circulation and just prior to pulling pipe for the logging run, and it is believed that the mud samples were fairly representative of the resistivity of the mud in the bore hole at the time of logging. Before the results of the test are reviewed, the normal apparent-resistivity recording might be considered.

The so-called "shallow penetration curve," otherwise known as the normal apparent-resistivity curve, can be made by either current or potential measurements. In current measurements, a single electrode is employed down the hole and the other electrode may be the sheath of the cable. Because of the long length of the sheath electrode, the current density along the cable is very low while at the electrode down the hole, the current density is high because the current is emanating from a so-called point. The current density decreases inversely as the square of the distance from its source, $I/4\pi d^2$, and hence most of the measured changes will occur in a comparatively small imaginary sphere surrounding the point electrode. Accordingly, the drilling fluid, besides the medium by which the measurements are made, will have a large effect on the intensities if an average size bore hole is considered, as the greatest part of the potential drop will take place near the current electrode. Comparable potential measurements are usually made by spacing a potential electrode near the current electrode and a surface ground is ordinarily used for the other potential electrode. Therefore, the bore hole fluid will also greatly affect such potential measurements.

In studying the effect of the mud on the intensities of the measurements, dense formations were compared at shallow depths so that invasion would not be a source of error. Determinations where invasion is a factor would be inconclusive as it would not be known to what extent the drilling mud invaded the formation.

In one well in Louisiana, five logs of the same section were made over a two-week period and the mud was successively 3.15, 2.44, 1.79, 0.90 and 0.34 ohm-meter at 106°F. When the five runs of the normal apparent-resistivity curves were compared at the same sections, it was found, taking 1 as the sensitivity in the 0.34 ohm mud, the relative intensities were respectively 8.0, 4.0, 2.45, 1.4, and 1.0, or the normal apparent-resistivity curve was eight times as sentitive in the 3.15 ohm mud as it was in the 0.34 ohm mud. The diameter of the bore hole was the same during all five runs of this test. However, if the bore hole diameter should be increased and the mud resistivity remain constant, it is believed the intensities would be affected as the bore hole would be a larger part of the investigated area and a greater portion of the potential drop would take place in the bore hole.

The wider spaced apparent-resistivity curves could not be used for determinations in this particular well because there were no peaks large enough to measure accurately. In another well, however, where

there was no evidence of invasion, the third curve was identical over a period of four months, although the mud resistivity changed from 2.50 ohm-meter at 88°F. on Run No. 1 to 1.20 ohm-meter at 89°F. on Run No. 2. Again, in another case, measurements were taken over the same sections ten days apart. The mud resistivity was lowered from 4.40 ohms at 73°F. to 0.32 ohm at 72°F. and on both runs the third curve repeated for 2000 feet except through one fifteen-foot sand. Evidently, this fifteen-foot sand was invaded by the drilling fluid.

It would seem from theoretical considerations that the various apparent-resistivity curves should not be all affected in the same proportion as the mud resistivity is changed, and it appears this test substantiates that belief, because when the wider spaced curves were run, changes in mud resistivity had comparatively little effect. Of course, the mud resistivity didn't vary over a particularly large range, and it is entirely possible that if the changes were greater—say, from 15.0 ohm-meter to 0.01 ohm-meter,—the intensities of even these curves would be affected. For average mud changes, it is believed that no corrections would be necessary, but for a greater range as mentioned above, it might be necessary to establish intensity correction curves for the wider spaced apparent-resistivity curves.

The natural potential curve is practically always recorded in the same manner but the theory of this measurement is a moot question. It is not the intention of this paper to discuss the theory of this recording, but it may be said that the diameter of the hole seems to have little effect on the intensity of this curve while the mud resistivity exerts an important influence. In the well on which five runs were made, the natural potential curve was affected as follows: Again using 1 as the sensitivity in 0.34 ohm mud, the relationship was 3.3, 2.0, 1.41, 1.1, and 1.0, or the natural potential curve was 3.3 times as sensitive in the 3.15 ohm mud as it was in the 0.34 ohm mud.

Thus, it may be seen that while the resistivity of the drilling mud exerted an important influence on the natural potential curve, it had still a greater effect on the normal apparent-resistivity curve but comparatively little effect on the wider spaced apparent-resistivity curves.

These data indicate that the apparent-resistivity curves might often have little relationship to one another. For example, if a homogeneous formation is considered, the thickness of which is much greater than the electrode spacing and the drilling mud is the same resistivity as the formation, the apparent-resistivity curves, according to a re-

sistivity calibration, should have the same intensity in an impervious formation. However, if the mud was changed, it has been shown that the curve relationship would change, therefore, the use of a single calculated resistivity calibration for all curves is basically incorrect. Such calibration should never have been attempted. It would be better to calibrate the curves in millivolts and to furnish the electrode spacings and the current as additional information.

If an ideal formation such as described above was always available, this would be a way in which to match the sensitivities of the apparent-

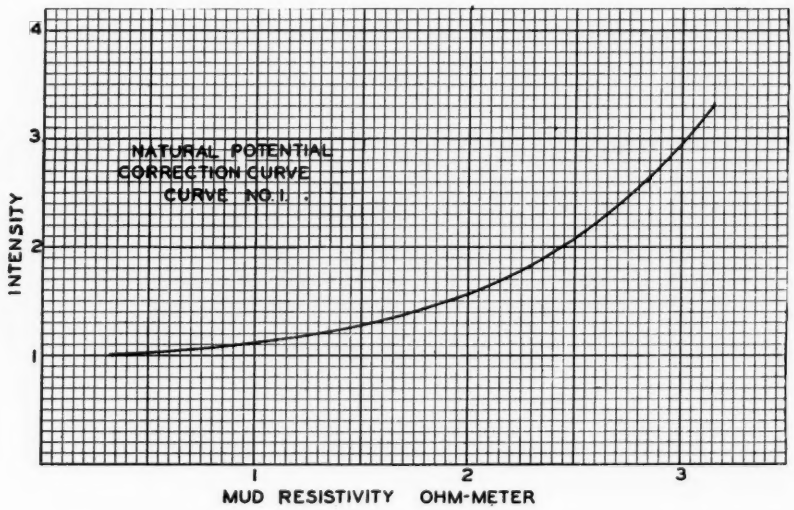


FIG. 1.

resistivity curves, but this is rarely possible so another method must be established.

The normal apparent-resistivity curve should be used mainly for correlation, differentiating between sands and shales and picking the tops and bottoms of formations but in low resistivity muds, it is some times difficult to accomplish this. The wide spaced apparent-resistivity curves cannot be used for these purposes because such curves measure an average of usually many formations and due to this heterogeneous condition and wide electrode spacings, there is often no relationship in the depth of such curves to the depth of the normal apparent-resistivity curve. Furthermore, only an averaging apparent-resistivity is obtained. The true resistivity cannot be determined because all the electrodes are not in a homogeneous medium and furthermore, the

drilling mud which is the means by which the electrical measurements are made possible, is usually of a different resistivity than the formation. However, if there is a homogeneous formation surrounding the measuring system, the thickness of which is much greater than the distance penetrated by the drilling fluid, the calculated apparent resistivity will be close to the true resistivity—provided that the correct spacing of electrodes is employed.

In Figs. 1 and 2 the results of the five runs in the same well were plotted with mud resistivity as abscissae against intensity as ordinate

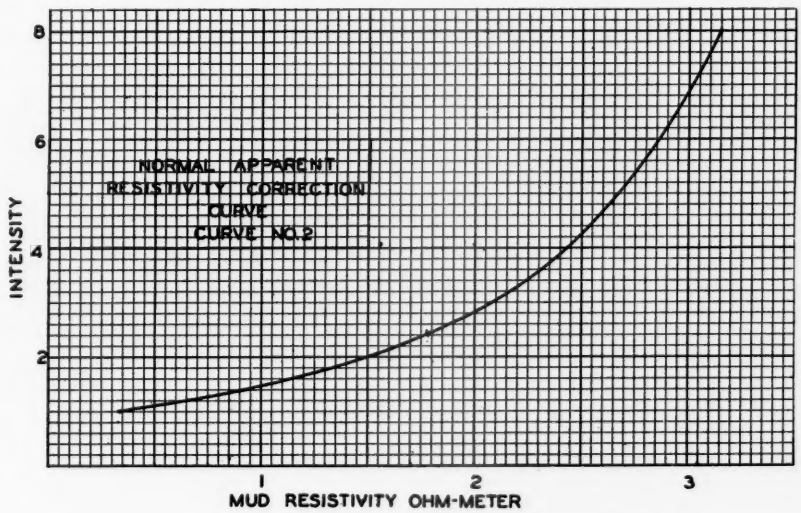


FIG. 2.

both for the natural potential curve and the normal apparent resistivity curve (correction curves Nos. 1 and 2) and from the resultant curves, the relative intensities of measurements in the same well on successive runs in different resistivity muds could be ascertained before examining the next run. It is regretted that the resistivity of the mud did not vary over a wider range so that the correction curves would cover all conditions, but such additional information could be derived through a fairly simple test program.

It is possible also to use these correction curves as a check to see if the mud resistivity was correct if two runs were made over the same section in different resistivity mud, but this is only possible if one of the two mud samples was approximately correct. If the true mud resistivity was known, the sensitivities for the normal apparent-resistiv-

ity and natural potential curves could be pre-selected from the relative intensity correction curves so that even if the mud resistivity was extremely low, electrical logs of adjacent wells would be more comparable. This should be helpful as either the natural potential curve or the normal apparent resistivity curve, or both, are generally used for correlation. In extremely low resistivity mud the natural potential curve is often worthless. Therefore, the normal apparent-resistivity curve alone must be used for correlation as well as its ordinary uses of differentiating between sands and shales and picking the tops and bottoms of formations. By compensating for low resistivity mud the normal apparent-resistivity curve intensities could be amplified so as to be comparable to the intensities of such a curve made in average resistivity mud. This would not only make it easier to pick the tops and bottoms of formations, but would assist in correlation, as anomalies often present on this recording in normal resistivity mud, would again be evident and more definite correlation could be made instead of depending on the haphazard method of comparing in effect, geometric figures.

The relative intensity correction curves could also be used for compensating for extreme mud resistivity changes in the same well on successive runs so the entire log would be more relative.

The intensities of logs of different wells in the same field are often compared and conclusions drawn although the mud resistivity is seldom considered. If any comparative determinations are ever to be derived, the true drilling mud resistivity must be known, the correct temperature noted, and the natural potential and normal apparent-resistivity curves at least, corrected in intensity for the same resistivity mud at the same temperature. Of course, this relationship will not necessarily hold true for the entire well because the geothermal gradient may not be the same even in adjoining wells, but the relationship will be nearer correct than it is at the present time. If a recording thermometer is run at the same time the electrical log is made then the approximate temperatures would be known at the various depths in different wells and the intensity relationships could be corrected more accurately. The mud samples may be tested for resistivity at the same temperature by actual measurements or for general purposes it may be said the mud resistivity will decrease approximately two per cent per degree F. increase in temperature.

It is recommended that the mud samples be taken always just prior to stopping circulation and given to the logging crew when they

reach the well. The drilling mud must be adequately circulated before taking the sample so that the mud is homogeneous throughout the entire column.

If intensity corrections are to be made, large variations in the bore hole diameters must be considered for the normal apparent-resistivity curves, and possibly correction curves established, but it seems this factor can be disregarded in corrections of the natural potential curves.

It is believed the relative intensities of electrical logs would be more comparable and interpretation errors minimized if corrections were made for changes in the resistivity of the drilling mud but such a procedure could only be followed if the method of taking the mud sample was standardized so it would be certain the mud sample was indicative of the mud in the bore hole at the time of logging.

RADIOACTIVITY ANALYSES OF OIL WELL SAMPLES*

BRUNO PONTECORVO†

ABSTRACT

A laboratory method of analyzing the radioactivity of rock samples is described in which the laboratory tests are designed to simulate the conditions which prevail when radioactivity logs of wells are made. Thus the radioactivity of samples may be correlated with the results of such well logs and their interpretation improved thereby.

The radioactivity of rock samples has been studied considerably since the discovery was made that very small amounts of radioactive elements are always present in matter. Recent accurate measurements on sedimentary rocks have been performed using the "emanation method." A critical and complete discussion of the subject matter, including an extensive bibliography may be found in a recent paper of Evans and Goodman.[1] Radioactivity logging of oil wells[2] gives a curve of the total gamma activity of the rocks in a well versus depth. The present paper describes a method of analyzing the radioactivity of samples which was developed in our laboratory *with the purpose of obtaining information useful for the interpretation of radioactivity well logs*. Of course, it is also quite desirable to have the means for predicting the type of radioactivity logs in a given area from a study of the sample radioactivity of this area.

In order to develop a method of correlating radioactivity logs with the radioactivity of samples, it must be remembered that:

First, the radioactivity well-logging instrument is affected only by gamma rays emitted from formations, and not by alpha and beta radiations. On the contrary, in the laboratory we may measure gamma, beta, and alpha rays from samples.

Second, the only radioelements which in practice contribute to radioactivity logs are: the uranium family, the thorium family, and potassium. Uranium and thorium are assumed to be in equilibrium with all their products.

* Presented at the Annual Meeting, Houston, Texas, April 2, 1941.

† Well Surveys, Inc., Tulsa, Oklahoma.

[1] R. D. Evans and C. Goodman, Bulletin of the Geological Society of America, vol. 52, No. 4, p. 459 (1941).

[2] G. H. Westby and S. A. Scherbatskoy, *Oil and Gas Journal*, February 22, 1940, p. 62. W. G. Green and R. E. Fearon, GEOPHYSICS, vol. 5, No. 3, p. 272 (1940). W. L. Russell, *The Oil Weekly*, November 11, 1940.

Third, the quantity of rock affecting the survey instrument is exceedingly large. On the contrary, for obvious practical reasons, this is not true in the case of samples. The fact that the size of the sample is inherently small, and the quantity of rock represented by well logging exceedingly large is the most serious source of difficulty in correlating sample measurements with radioactivity well logs.

Difficulties occur not only because the intensity of the gamma radiations from a small sample is very weak, but because the gamma radiation emitted by rocks has a very complicated spectrum caused by different components of the uranium family, the thorium family, and potassium.

Every component of the radiation has a different weighting factor for its effect on any gamma ray detector, which depends upon the thickness of the detecting instrument walls, and possible filters, such as casing, and also upon the geometrical conditions and the amount of rock present.

In general, in a well, the complex gamma radiation will be in equilibrium with its secondary Compton gamma radiation. This will not be the case for all the components if we measure the activity of a small rock sample.

It can be said that the well logging instrument has a greater weighting factor than a sample instrument for radioelements emitting gamma rays of high quantum energy. This assertion is not in conflict with the fact that, because of the degradate radiations, gamma rays which are actually recorded in the sub-surface instrument are on the average softer than those recorded by a sample instrument.

In order to correlate the measurements in a well and the measurements on samples, we first make a sample measurement exactly comparable with a well measurement by reproducing the well conditions in an "artificial well" (Fig. 1) in the laboratory, using very large amounts of rock. We prepare very large samples containing only the uranium family, only the thorium family, and only potassium, and then determine in a calibration measurement the ionization produced in the logging instrument by the separate components.

The correlation of sample radioactivity measurements with radioactivity well logs then becomes essentially the problem of measuring in any sample the separate amounts of uranium family, thorium family, and potassium. This has been done by a method which is considerably less sensitive than the emanation methods, but which has the advantage of not destroying the samples. Furthermore, the emana-

tion method obviously cannot give the analyses of potassium which are of primary importance for our purpose. Because of the small sensitivity of the present method, we use it only for the strongly active samples (see below).

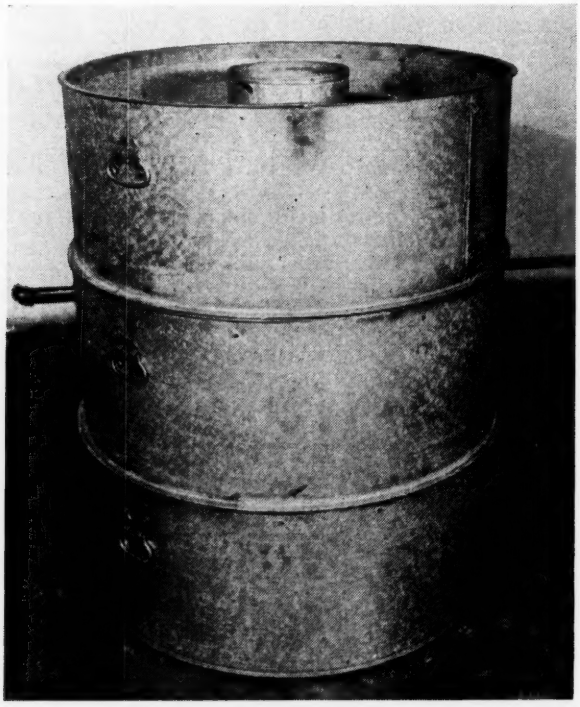


FIG. 1. Artificial well.

The present method consists in measuring the activity of a sample with three Geiger-Mueller counters, No. 1, No. 2, and No. 3 (Fig. 2). To every counter corresponds a standard sample container No. 1, No. 2, and No. 3. The container has an annular shape and is placed around the counter. The thicknesses of the inner wall of the containers (including the wall of the counter) are:

Geiger Counter +Container	*Wall Thickness in Aluminum Equivalent*	*Amount of Sample Used*	*Radiation Chiefly Detected*
No. 1	7 mm.	280 grams	Gamma
No. 2	0.6 mm.	70 grams	Beta+Gamma
No. 3	0.1 mm.	18 grams	Beta

It is clear that the counter No. 1 will record only gamma rays, counter No. 3 practically only beta rays, and counter No. 2 will record gamma and energetic beta rays together, with weighting factors for the thorium family, uranium family, and potassium which have to be determined only once.

These weighting factors are obtained in a calibration measurement, by determining the activity in each counter, of three artificial samples:

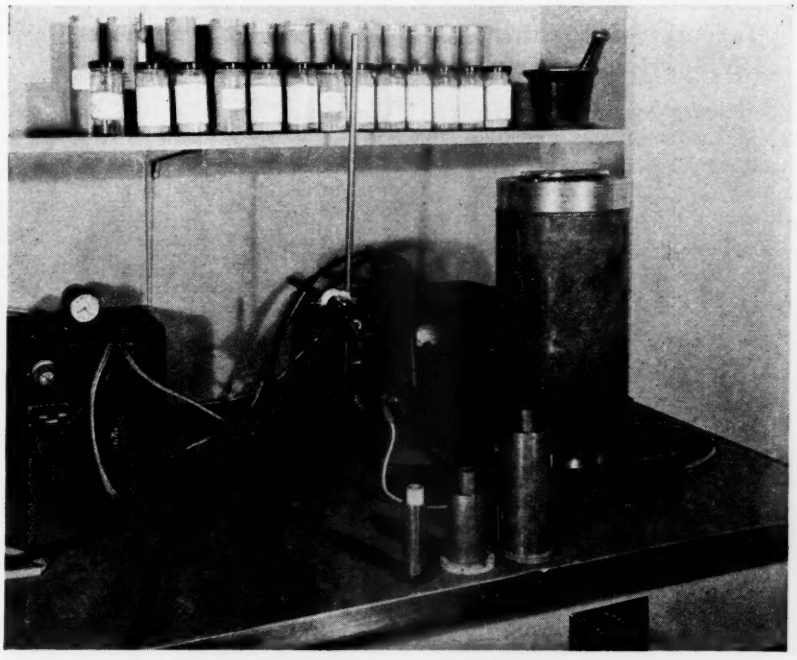


FIG. 2. Containers 1, 2, 3, and Geiger Counter shielded by lead.

the first containing quartz sand plus Carnotite, the second containing quartz sand plus Monazite, the third containing quartz sand plus potassium chloride.

Using the calibration data, the amount of thorium, uranium, and potassium in any sample can be obtained from the simple solution of a system of three linear equations with three unknowns. In fact, the ratio of the number of beta rays to the number of gamma rays is very different for potassium and the uranium and thorium families, and on

the other hand, the spectra of beta rays from various radioelements present considerable differences.[3]

Because of the small sensitivity of the present method, we can use it only for the "strongly active" samples, in which we are especially interested. We define conventionally "strongly active" samples as those which give >2 impulsions per minute above the background (20 impulsions/minute) in our gamma counter: this figure would correspond, for a sample containing *only* the uranium family, to 5×10^{-12} gram of radium per gram of rock.

In conclusion the writer wishes to thank Mr. R. E. Fearon and Mr. T. H. Gilmartin for their collaboration in this work.

[3] See, for instance, E. Rutherford, J. Chadwick, C. D. Ellis, Radiations from Radioactive Substances, Cambridge University Press, 1930, p. 408; and P. Curie, Radioactivité, Hermann Editeur, 1935, vol. I, p. 292.

PATENTS

ELECTRICAL PROSPECTING

U.S. No. 2,256,742, J. J. Jakosky, Iss. 9/23/41, Appl. 6/13/39.

Electrical Exploration of the Subsurface—A method and device in electrical prospecting whereby a moving electrode system is attained by successively contacting each of a plurality of spaced ground-electrodes or successively contacting the ground by a plurality of moving electrodes in such manner that at least one electrode contact is always maintained. For example, a flexible cable attached to each of a pair of metal-soled shoes worn by a line-man walking along the line of traverse would embody the idea of the moving electrode disclosed.

U.S. No. 2,263,097, J. A. Marchand, Iss. 11/18/41, Appl. 5/8/39. Assign. Fifty-five per cent to Bailey Balken.

Geophysical Prospecting—A method of electrical prospecting comprising the measurement of the potential produced by telluric currents between a central point and a plurality of points spaced equidistant about the central point, and measuring the current which flows through a fixed resistance between the same points. Repeating the measurements at other sets of points permits the location of subsurface structures from the pattern of current distribution.

U.S. No. Re. 21,914, D. S. Muzzey, Jr., Reiss. 9/30/41, Appl. 5/19/41. Assign. Shell Development Company.

Commutation System—For electrical prospecting; a commutator and circuit designed to operate at low frequency. Two potentiometers are provided, one to balance out the natural ground potentials at the potential electrodes and the other to balance out the commutated potential due to the alternating potential impressed on the current electrodes. Automatic depolarizing means is provided.

GEOCHEMICAL PROSPECTING

U.S. No. 2,261,764, Leo Horvitz, Iss. 11/4/41, Appl. 11/14/39. Assign. E. E. Rosaire.

Geochemical Prospecting—A method of exploration for carboniferous deposits and of well logging comprising the quantitative determination of carbon monoxide evolved from samples taken from bore holes.

GRAVIMETRIC PROSPECTING

U.S. No. 2,255,876, D. H. Clewell and H. A. Maeder, Iss. 9/16/41, Appl. 3/6/40, Assign. Socony-Vacuum Oil Co.

Gravity Meter—In gravity meters of the type that have their mass supported by bifilar torsional elements; primarily a design of suitable chucks and adjusting means for these suspensions so as to minimize drift and related difficulties traceable to distortions of the suspensions at or near their point of support.

U.S. No. 2,258,613, F. M. Kannensteine and F. M. Floyd, Iss. 10/14/41, Appl. 5/11/38. Floyd assignor to Kannenstine.

Measuring Instrument—A measuring instrument capable of being used as a gravity meter in which a mass is supported by a cantilever beam so tapered that stresses are

uniform along its length. The displacement of the mass may be measured by determining the electrical capacitance of the condenser formed by the mass and base.

U.S. No. 2,263,096, J. A. Marchand, Iss. 11/18/41, Appl. 9/2/38. Assign. Fifty-five per cent to Bailey Balken.

Gravity Measuring Instrument—A tubular pendulum is suspended from a horizontal beam pivoted at the center with a weight above one end of the beam, a spring attached to the other end exerting a restoring force. The period is adjusted by raising the weight or point of attachment of the spring. The changes in gravity are measured by observing the changes in the range of movement of the pendulum. Your reviewer is unable adequately to analyze the operation of this device which is a hybrid pendulum—astatized gravimeter.

U.S. No. 2,265,011, Sidney Siegel, Iss. 12/2/41, Appl. 7/26/39. Assign. Westinghouse Electric and Manufacturing Co.

Sensitive Device for Measuring Forces—A mass is suspended by a conducting nonmagnetic fiber in a magnetic field at right angles to the fiber. The output of an amplifier is connected across the fiber while the amplifier input is connected to a suitable pickup coil adjacent to the fiber such that the fiber is maintained in oscillation at its natural frequency determined by the density of the fiber and the weight of the attached mass. The resonant frequency can be determined by comparison with a suitable standard such as a piezo-electric oscillator.

MAGNETIC PROSPECTING

U.S. No. 2,261,030, W. P. Jenny, Iss. 10/28/41, Appl. 12/27/40.

Micromagnetic Prospecting Device—A magnetometer, with which to measure the magnetic gradient, is constructed similar to the Eotvos torsion balance the lower weight being replaced by a horizontally suspended magnet. The weight of the magnet is offset by the buoyant force of a surrounding liquid, which permits the counterweight on the beam to be reduced. This is designed to reduce the effect of gravitational forces.

SEISMOGRAPH PROSPECTING

U.S. No. 2,257,423, J. D. Malmqvist, Iss. 9/30/41, Appl. 6/20/39. Assign. Bolidens Gruvaktiebolag, Stockholm, Sweden.

Determining the Velocity of Elastic Waves in the Ground—Utilizing a cathode ray tube in which A.C. of known frequency is applied to the vertical deflecting plates and superposed thereon, the shot moment and succeeding impulses picked up by a geophone or like transducer. A suitable sweep frequency is applied to the other deflecting plates to produce the usual rectilinear wave pattern. A camera records the oscillograph trace and a measure of the time interval between the shot-moment pulse and the later geophone impulse, in terms of the known frequency permits calculation of wave velocity.

U.S. No. 2,257,859, E. E. Rosaire and F. M. Kannenstine, Iss. 10/7/41, Appl. 3/8/37. Assign. E. E. Rosaire.

Method and Apparatus for Recording Waves—Method and apparatus for seismic prospecting, depth sounding, and sound ranging. The principle is similar to F. Rieber's

sonograph method. Means are provided for the usual recording of separate traces from each of a plurality of spaced geophones. In addition a network provides for the summation of all channels with adjustable delay circuits or equivalent means in each channel. The delay producing the maximum amplitude of the composite trace for a given reflected pulse determines the direction and dip of the reflecting surface or the direction of the sound source in sound ranging.

U.S. No. 2,260,217, E. A. Eckhardt and G. Muffly, Iss. 10/21/41, Appl. 3/14/39. Assign. Gulf Research & Development Co.

Method of and Apparatus for Seismograph Prospecting—A method of seismograph prospecting utilizing groups of seismic detectors but provided with a switch and control circuit permitting the first seismic impulse to be recorded from only one detector while later reflected impulses from all the detectors of the group may be combined and recorded.

U.S. No. 2,264,098, LeRoy C. Pasley, Iss. 11/25/41, Appl. 11/3/37. Assign. National Geophysical Company.

Deflection Limiter for Galvanometers—A circuit which is designed to limit the voltage applied to a galvanometer but not to affect the voltage up to the desired maximum, utilizes a biased circuit usually comprising a biased copper-oxide rectifier which shunts the primary of the input transformer leading to the galvanometer whenever the input voltage exceeds the biasing voltage. This permits first breaks to be sharp without excessive deflection of galvanometer. After elapse of time about equal to the time-delay of the usual A.V.C. a relay cuts out the shunt circuit and thereafter the A.V.C. is the sole limiter in action.

WELL LOGGING

U.S. No. 2,255,295, L. C. Miller, Iss. 9/9/41, Appl. 5/18/39.

Inclination Indicating Device—A pendulum device to indicate the inclination of a well bore utilizing a light concentrating means suspended on a universal joint and so arranged to focus a beam of light on a light-sensitive element below it. Automatic means lights and extinguishes the light at the top of the concentrating means.

U.S. No. 2,255,754, L. C. Beers, Iss. 9/16/41, Appl. 3/8/39. Assign. Lane-Wells Company.

Multiple Record Electrologging of Wells—A method and apparatus for obtaining, with a single-conductor shielded cable and with a single trip into the well, all the curves ordinarily obtained in electro-logging of wells. Slip ring commutators are utilized so as to energize the current electrodes. Rectifiers permit the recording of potentials from the potential electrode. At short intervals the current electrodes are deenergized and spontaneous potentials are measured.

U.S. No. 2,259,904, B. F. McNamee and F. Rieber, Iss. 10/21/41, Appl. 1/17/38.

Method and Apparatus for Logging Bore Holes—By lowering in the bore hole at a constant rate a periodically excited consequent-poled electromagnet of relatively short length there is induced in the adjacent sediments a corresponding pattern of space-alternating permanent magnetization, the intensity of which will vary with variations

in susceptibility and retentivity of the sediments. The same electromagnet or an equivalent device, in connection with a suitable amplifier, then traverses the hole whereby the magnetic pattern is reproduced as an alternating emf which is recorded on a suitable oscillograph. The envelope of the recorded A.C. depicts the magnetic properties of the sediments traversed.

U.S. No. 2,260,562, L. Dillon, Iss. 10/28/41, Appl. 12/13/37. Assign. Union Oil Co.

Process and Apparatus for Core Sample Orientation—The core sample is rotated at the center of an inductor coil. The induced alternating emf is synchronized with an alternating emf induced by an auxiliary magnet rotating on the same shaft as the sample but beyond the range to affect the first coil. The application of the two emfs to a cathode ray oscilloscope produces a Lissajou figure permitting the orienting of the sample.

U.S. No. 2,262,934, D. Herring, Iss. 11/18/41, Appl. 6/10/39. Assign. Sperry-Sun Well Surveying Co.

Well Surveying Method—Using a gyroscopic well surveying instrument errors caused by random drift of the gyro element are eliminated by the expedient of holding the survey instrument stationary in the hole at appropriate intervals and for a sufficient period of time to record the rate of drift. If several such records are obtained, a gyro-drift vs. time curve may be plotted and applied as a correction to the survey record.

U.S. No. 2,263,108, R. W. Stuart, Iss. 11/18/41, Appl. 7/16/40. Assign. Stanolind Oil and Gas Co.

Logging Wells During Drilling—A test for crude oil is made continuously by passing the returning mud stream under an exciting source of ultraviolet light and observing the amount of fluorescent light. Means for recording the amount of fluorescence is provided by a photoelectric unit.

U.S. No. 2,264,318, F. W. Lee, Iss. 12/2/41, Appl. 4/8/38.

Geophysical Surveying—A method and device for surveying a bore hole. The electrical constants of contiguous sediments are compared by passing a pulsating current through an exciting coil and noting the potentials induced in two pickup coils located coaxially one on each side of the exciting coil.

GENERAL

U.S. No. 2,258,700, H. G. Doll, Paris, France, Iss. 10/14/41, Appl. 5/12/37. Assign. Schlumberger Well Surveying Corp.

Recording Apparatus—A method and apparatus for recording deflections of an instrument which normally will pass beyond the edge of the recording paper without sacrifice of sensitivity. Either several light beams projected on a single mirror on the moving element or a single light beam projected on a mirror with several facets may be utilized. The resulting images are so adjusted that when one image is about to pass beyond one edge another is passing onto the opposite edge.

U.S. No. 2,262,965, A. H. Riney and J. D. Durkee, Iss. 11/18/41, Appl. 12/27/38. Assign. Phillips Petroleum Company.

Surveying System—A system utilizing the directive transmission of ultra high frequency radio waves, an equi-signal zone beam such as produced by crossed loops being used to replace the telescopic line of sight. The distance between points may be meas-

ured, similar to stadia measurements, by determining the distance between points of equal intensity in an equi-signal zone beam at the distant point or may be measured by triangulation using the beams for sighting. The stations can be hidden from each other.

The first application of geophysics to war is described in Froude's "The Reign of Edward the Sixth." In Chapter 3, page 114 (Everyman's Edition, Dent, 1909), the historian is describing the siege of Exeter which was defended by loyal troops, and which the rebels attempted to capture by digging tunnels under the walls.

Froude states—"As the rebels mined, the citzens counter-mined. Where the assailants were suspected to be at work, an adroit engineer detected their presence underground by the vibration of a pan of water above their heads, and they were blown up or drowned in their holes."

The siege was lifted in August, 1549.

It is a pity that the name of this pioneer geophysicist has not been preserved, but it would appear that he was probably not an important scientist of that day.

P. Weaver

CONTRIBUTORS

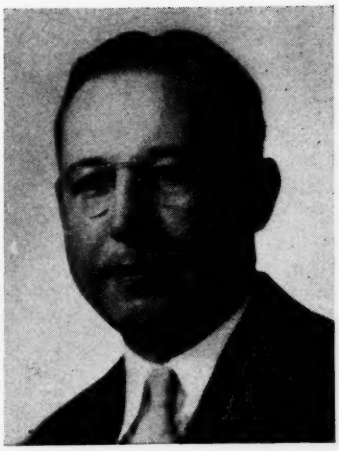
JOSEPH L. ADLER

JOSEPH L. ADLER received his B.S. degree from the University of Chicago in 1917 and his Ph.D. degree from the same university in 1930. After a year's service in the U. S. Army during the World War he devoted seven years to the practice of oil geology in various parts of North and South America interspersed with periods of residence in the Graduate School at the University of Chicago. From 1927 to 1934 he served on the faculty of Michigan College of Mining and Technology, where he first became engaged in geophysical work in 1928. In 1934 he became associated with Independent Exploration Company with whom he still serves. Since his entry into the field of geophysics his principal activity has been in magnetic and seismic exploration. Dr. Adler is a fellow of the American Association for the Advancement of Science and the American Geographical Society, and is a member of the A.I.M.M.E., the A.A.P.G., the American Geophysical Union, and the Society of Exploration Geophysicists.

M. C. BOWSKY received his B.S. degree in 1928. He has been engaged in geophysical work since 1928 when he was connected with the Taumac Corporation. In 1933, he joined the Swedish-American Prospecting Company. In 1935, he became associated with Lane-Wells Company by whom he is still employed. Mr. Bowsky's work has been primarily with research on surface electrical prospecting methods, and the development and investigation of electrical logging equipment and methods. He is a member of the A.I.M.E., a member of the Southwestern Sub-Committee of the A.P.I. on Core Analysis and Electrical Logging, and a member of the Society of Exploration Geophysicists.

M. C. BOWSKY

THOMAS A. ELKINS received his B.S. degree in 1927 and an M.S. degree in 1931 from Carnegie Institute of Technology. He has been connected with the Gulf Research & Development Company since 1930, with the exception of a period of study at Princeton University, from which he received an A.M. degree in mathematics in 1935. Mr. Elkins has devoted his attention primarily to mathematical and statistical problems arising in the interpretation of gravity and magnetic prospecting data. He is a member of the American Physical Society, the Physical Society of Pittsburgh, and the Society of Exploration Geophysicists.



THOMAS A. ELKINS

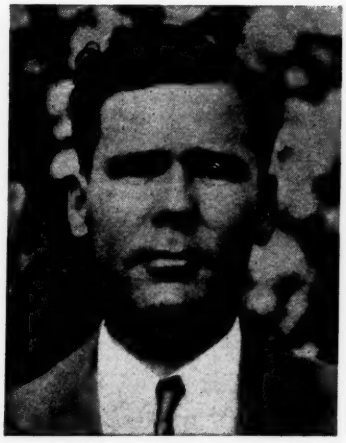
C. A. HEILAND

C. A. HEILAND received his D.Sc. degree from the University of Hamburg in 1923. Prior to that, in 1921, he did geophysical work for the State of Hamburg and in 1922 for the Raky Drilling Company. In 1924 he took charge of the geodetic and geophysical department of the Askania Company in Berlin, went to the United States as their representative, and introduced automatic torsion balances and Schmidt magnetometers. In 1926 Dr. Heiland organized the Department of Geophysics at the Colorado School of Mines. He joined the U. S. Bureau of Mines in cooperative study of geophysical methods in 1927. Taught a summer course in geophysics at Columbia University in 1929. Various engagements by oil and mining companies in consulting capacity were followed in 1934 by the organization of the Heiland Research Corporation which has since done consulting work with seismic and electrical methods, has constructed seismic, electrical, and other geophysical equipment for oil and mining companies and various government agencies. Has been Section Chief for geophysics of the Annotated Bibliography of Economic Geology since 1928, is author of the articles on geophysics in recent editions of the Encyclopaedia Britannica and Encyclopaedia Americana, as well as nearly ninety technical and semi-technical publications. In 1940, he published the book "Geophysical Exploration." Dr. Heiland is Collaborator in Seismology of the U. S. Coast and Geodetic Survey, member of the American Geophysical Union, the Seismological Society of Ameaica, the A.A.P.G., the A.I.M.M.E. (Vice-Chairman, Geophysical Committee), and a member of the Society of Exploration Geophysicists.

DE FORREST METCALF

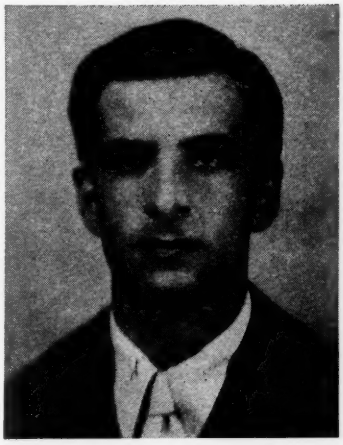
DE FORREST METCALF received the B.S. degree from the University of Texas in 1937, at which time he joined the Geophysical Department of the Humble Oil and Refining Company. While with this organization his work consisted in exploration, research, and developmental activities, the latter in connection with electrical prospecting methods. He is now with the Engineering Department of the E. F. Johnson Company. Mr. Metcalf is a member of the Society of Exploration Geophysicists.

E. F. NEUENSCHWANDER received the B.S. degree from the University of Texas in 1932, and did post-graduate work from 1932–34. He joined the Geophysical Department of the Humble Oil and Refining Company in 1934. His work consisted in exploration, research and developmental activities, the last five years in connection with electrical prospecting methods.



E. F. NEUENSCHWANDER

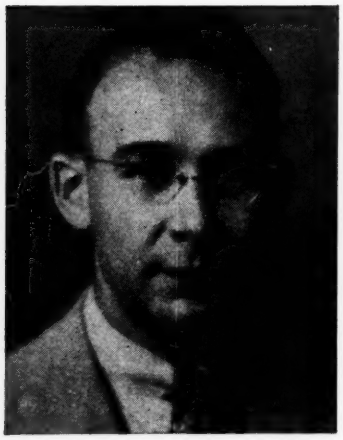
BRUNO PONTECORVO received his Ph.D. degree in physics from the University of Rome in 1933. For the three years subsequent to obtaining this degree, he worked in the field of nuclear physics in the laboratories of the University of Rome. In 1936 he went to Paris and worked in the Curie Laboratory at the Institute of Radium. The latter portion of the time he was in Paris he continued his work in nuclear physics at the College de France. In September, 1940, he came to the United States to join the staff of Well Surveys, Inc., of Tulsa. At this time he is engaged in research work connected with the problems of relating radioactivity and geology.



BRUNO PONTECORVO

ARNOLD J. F. SIEGERT

ARNOLD J. F. SIEGERT received his Ph.D. degree in theoretical physics in 1934, working under Prof. W. Heisenberg at the University of Leipzig, Germany. From 1934 to 1936 he held a fellowship of the Lorentz Foundation in Leiden, Holland, working on the quantum mechanical explanation of paramagnetic effects. From 1936 to 1939 he taught at Stanford University, California, and was engaged in research on problems of nuclear physics and worked on the Klystron project. In 1939 he became associated with The Texas Company, Houston, Texas, by whom he is now employed as a mathematical physicist. Dr. Siegert's work has consisted primarily in developing methods of evaluation and interpretation of gravity data, and in theoretical developments concerning the application of radioactivity methods to exploration and refining problems. He is a member of the American Physical Society.



ALEXANDER WOLF

ALEXANDER WOLF received the degree of B.S. in E.E. from the University of Pennsylvania in 1924, and Ph.D. in Physics from the California Institute of Technology in 1933. From 1926 to 1930 he was engaged in seismic exploration for the Sun Oil Company. Since 1933 he has been in charge of the Geophysical Laboratory of The Texas Company in Houston. Dr. Wolf is a member of the American Physical Society and the Society of Exploration Geophysicists.

THE SOCIETY ROUND TABLE

ANNOUNCEMENT OF ANNUAL MEETING—1942

A meeting of the Executive Committee of the Society of Exploration Geophysicists was held in Houston on January 15 to discuss the advisability of proceeding with plans to hold the Annual Meeting. It was the unanimous view of the committee that a meeting should be held but that under the circumstances confronting us this year the ordinary type of meeting to which we are accustomed would not be appropriate; accordingly, all social functions will be eliminated and the program oriented to the fullest possible degree to reviewing the participation of geophysics in the national war effort. The A.A.P.G. also propose to proceed with their arrangements for a meeting and they have agreed that most of their sessions should be held jointly with us.

In accordance with this decision, the Annual Meeting will be held at the Cosmopolitan Hotel in Denver, Colorado, on April 22–24 inclusive. A tentative schedule has been arranged as follows:

Tuesday, April 21	P.M.	Registration, Executive Committee Meeting
Wednesday, April 22	A.M.	Joint sessions with
	P.M.	A.A.P.G.
Thursday, April 23	A.M.	Joint sessions with
	P.M.	A.A.P.G.
Friday, April 24	A.M.	Business Meeting, S.E.G. Technical Session
	P.M.	S.E.G. Technical Session

The Program and Arrangements Committee has been appointed as follows:

L. L. Nettleton	Atlantic Coast Area
A. B. Bryan	Tulsa Area
C. A. Heiland	Rocky Mountain Area
Henry Salvatori	Pacific Coast Area
J. H. Pernell	Dallas Area
D. S. Hughes	Houston Area
F. Goldstone	Houston Area (General Chairman)

The above Committee will contact a majority of members with a request for papers. Since we are holding only two technical sessions it will be possible to present only a limited number of papers. This should not discourage members from submitting suitable papers which could be read by titie and later published in GEOPHYSICS.

The Program Committee hopes to have the technical program formulated by the end of February and to have abstracts of the papers in their hands by early March in order that these may be released to the technical press well in advance of the meeting.

Houston, Texas
January 20, 1042

NOTICE PERTAINING TO CIVILIAN DEFENSE

Members of the Society of Exploration Geophysicists in the Third Railroad Commission District of the 8th Corps Area have been asked to join with the Gulf Coast Section of A.I.M.M.E., the Houston Geological Society and the Houston Chapter of A.P.I. in forming a technical committee for civilian defense as it pertains to the defense of oil and gas production. The officers of the Society who reside within this area heartily endorse this action and urge all members to avail themselves of this opportunity to render a very essential service. Should this movement spread to other areas, it is hoped that members of the Society will make their services available in those areas.

H. B. PEACOCK, *President*

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee has approved for publication the names of the following candidates for membership in the Society. This publication does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it to the Secretary within thirty days. (Names of sponsors are placed beneath the name of each nominee.)

ACTIVE

Robert Lee Geyer
Noyes D. Smith, F. B. Leedy, W. T. Green

Wilhelmus Johannes Cornelis Kau
D. R. Brown (Article III-D-1 of the Constitution)

Turner L. Kunkel
Louis A. Scholl, Jr., Roy L. Lay, C. C. Zimmerman

Howard Vernon McMurry
F. Goldstone, D. S. Hughes, M. O. Gibson

Joel Manuel Rich
George E. Wagoner, R. W. Gemmer, A. B. Bryan

James Edward Walker
F. Goldstone, D. S. Hughes, M. O. Gibson

ASSOCIATE

Ch'eng Yi Fu
C. A. Heiland, Dart Wantland, R. Maurice Tripp

Roy A. Hill
Sidon Harris, Garvin L. Taylor, Daniel Silverman

Robert William Jones
Charles A. Swartz, R. D. Wyckoff, E. A. Eckhardt

Anthony Peter Mehringer
H. M. Houghton, Andrew Gilmour, L. Y. Faust

John Whittaker Pertwee
L. K. Mower, F. Goldstone, F. A. Van Melle

STUDENT

Charles Winfield Oliphant
L. Don Leet

TRANSFER TO ACTIVE

W. A. Meszaros — R. Maurice Tripp

The ballot reprinted below was mailed to all active members of the Society of Exploration Geophysicists on December 13, 1941. Active members who failed to receive ballots may secure them by notifying J. F. Gallie, Business Manager, P. O. Box 2585, Houston, Texas. *Only active members who have paid 1942 dues are eligible to vote.*

OFFICIAL BALLOT

FOR THE YEAR APRIL, 1942—APRIL, 1943

For the Election of Officers for the

SOCIETY OF EXPLORATION GEOPHYSICISTS

Before voting, please note the following extracts from the Society Constitution:

Article V-A—Officers

1. **The officers of the Society shall be a President, a Vice-President, a Secretary-Treasurer, and an Editor. These, together with the Past President, shall constitute the Executive Committee and managers of the Society. Officers shall be elected for a term of one year with the exception of the Editor, who shall be elected for a term of three years.**
2. **. . . Each member shall cast one vote for each officer to be elected and shall return his ballot to the Secretary-Treasurer. Ballots to be valid must be enclosed in an envelope carrying on the outside the written signature of the member submitting the ballot, and must be received by the Secretary-Treasurer at his officially recognized address not later than ten days prior to the Annual Meeting. Only ballots received from members in good standing as of a date ten days prior to the Annual Meeting shall be valid . . .**

FOR PRESIDENT

FRANK GOLDSTONE	☐
A. B. BRYAN	☐
.....	☐

FOR VICE-PRESIDENT

HERBERT HOOVER, JR.	☐
R. D. WYCKOFF	☐
.....	☐

FOR SECRETARY-TREASURER

T. I. HARKINS	☐
F. F. REYNOLDS	☐
.....	☐

FOR EDITOR

RICHARD L. DOAN	☐
JOSEPH A. SHARPE	☐
.....	☐

After voting, place in accompanying official envelope, which should then be signed and mailed to the

SECRETARY-TREASURER,
W. M. RUST, JR.
P. O. Box 2180
Houston, Texas

NOMINEES FOR 1942–1943 EXECUTIVE COMMITTEE

The following short biographical sketches have been prepared in an attempt to acquaint members with the nominees appearing on the official ballot which was mailed out December 13, 1941.

FOR PRESIDENT

FRANK GOLDSTONE received his B.A. degree from Cambridge University, England, in 1922, and was awarded an M.A. in 1926. Post-graduate work was also done at the Royal School of Mines, London, England, 1928–1929. He first entered geophysics in charge of a torsion balance field crew in Borneo in 1923, and was transferred to the United States in 1926. He has served as Chief Geophysicist of the Shell Oil Co., Inc., since 1929. In 1934 he was elected Vice-President of the Society of Exploration Geophysicists (then the Society of Petroleum Geophysicists), and he was again elected to this office in 1941.

A. B. BRYAN received his B.A. degree in 1918, his M.A. in 1920, and his Ph.D. in Physics in 1922, all from the Rice Institute. From 1922 until 1935 he served as an instructor in physics at Rice; during this period he was also employed from time to time by the Humble Oil and Refining Company on various special projects in the field of geophysical prospecting research. In 1935 he was employed by the Carter Oil Company of Tulsa and was placed in charge of the geophysical research group which was then being organized. He continued in this capacity until April, 1937, when he was made Chief Geophysicist. He is a member of the American Physical Society, the American Geophysical Union, and the Society of Exploration Geophysicists.

FOR VICE-PRESIDENT

HERBERT HOOVER, JR., received a degree in Mining Engineering in 1925 from Stanford University, and subsequently received his M.B.A. in 1927 from Harvard. Since that time he has done consulting work in communications and exploration, and has been associated with Western Air Express, T. W. A., and the California Institute of Technology. Since 1934 he has been President of the United Geophysical Company and the Consolidated Engineering Corporation. He is a member of the American Institute of Mining and Metallurgical Engineers, the American Association of Petroleum Geologists, the American Institute of Radio Engineers, the Seismological Society of America, the American Association for the Advancement of Science, and the Society of Exploration Geophysicists.

R. D. WYCKOFF received his B.S. in E.E. at Michigan State College in 1920. After a short period as M.E. in the plant engineering department of the Ford Motor Company, one and one-half years on the E.E. staff at Michigan State College, and two years in general electrical engineering work at Lansing, Michigan, he joined the staff of the U. S. Bureau of Standards, Electrical Instrument Section, remaining for a three-year period. In 1926 Mr. Wyckoff entered the geophysical field with the Marland Oil Company in Oklahoma, and in 1929 joined the staff of the Gulf Research and Development Company, primarily to continue development of pendulum apparatus, and later in charge of the Physics Division. During the latter period he was associated with the development of gravimeters and general production research. In 1936 he again entered the Geophysics Division and from 1936 through 1939 was District Supervisor in the Gulf Research and Development Company's Houston office. Since that time

he has been a member of the geophysical staff at Pittsburgh. He is a Fellow in the American Physical Society, and a member of the Institute of Radio Engineers, the American Institute of Mining and Metallurgical Engineers, the American Petroleum Institute, the American Geophysical Union, and the Society of Exploration Geophysicists. He has served as Editor of GEOPHYSICS for the past three years.

FOR SECRETARY-TREASURER

T. I. HARKINS received his B.S. degree in 1927 from Louisiana State University. Upon graduation he entered the employ of the Geophysical Research Corporation, remaining with this corporation until 1932. He was in charge of the G. R. C. crew working for Gulf which was the first seismograph crew to map structure successfully by the reflection dip shooting method. In 1932 he resigned to assist in organizing the Independent Exploration Company. He served as Party Chief and Supervisor with this company until 1937, when he was elected President and General Manager. He was a charter member of the Society of Exploration Geophysicists, and is also a member of the American Association of Petroleum Geologists.

F. F. REYNOLDS received his B.S. degree in E.E. in 1928 from Rice. Following his graduation, he accepted employment with the Geophysical Research Corporation. He remained with G. R. C. until 1932, when he organized Seismic Explorations, Inc. He is President of Seismic Explorations, Inc. Mr. Reynolds is a member of the American Association of Petroleum Geologists, the American Association for the Advancement of Science, and the Society of Exploration Geophysicists.

FOR EDITOR

RICHARD L. DOAN received his A.B. in 1922 and his A.M. in 1923, both from Indiana University. He received his Ph.D. in 1926 from the University of Chicago. He served as an instructor in physics at Indiana in 1922–23, at Reed College, Portland, Oregon, in 1923–24, and at the University of Chicago in 1925–26. He was a National Research Fellow in 1926, and was the first to obtain X-ray spectra from ruled optical grating, which is the source of the present accepted value of electronic charge. From 1926 until 1933 he served with Western Electric Company, Manufacturing Development Division, Hawthorne Branch, working on magnetic materials; the last four years he was Department Chief. From 1933 until 1936 he was associated with Prof. A. H. Compton in the development and construction of instruments for studying cosmic rays. In July, 1936, he accepted employment with the Phillips Petroleum Company, Bartlesville, Oklahoma, and was placed in charge of Geophysical Research. He is now Associate Director of Research in charge of Exploration and Production Research. He is a member of the American Physical Society, the American Association for the Advancement of Science, and the Society of Exploration Geophysicists; an associate member of the American Association of Petroleum Geologists, and an applicant for membership in the American Institute of Mining and Metallurgical Engineers.

JOSEPH A. SHARPE received his B.S. in Physics in 1928 at the University of Arizona. He did graduate work at Arizona in 1928–30, and from 1930 until 1934 continued his work in physics, mathematics, and geology at the University of Wisconsin, receiving his Ph.D. in Physics from that school in 1934. Postdoctorate work in geophysics was taken at the Massachusetts Institute of Technology, where he was General Edu-

cation Board (Rockefeller Foundation) fellow. In 1927–28 Dr. Sharpe served as half-time computer in the Tucson Magnetic Observatory of the U. S. Coast and Geodetic Survey. From 1928 until 1930 he was an instructor in physics at the University of Arizona, and from 1930 until 1934 he held assistantships in physics, geology and geophysics at the University of Wisconsin. While at the latter school, he installed and operated the seismological observatory of the University. From 1935 until 1937 he served as Seismologist in the joint geophysical laboratory of the Stanolind Oil and Gas Company and the Western Geophysical Company. Since 1937 he has been Chief Physicist, in charge of research, for the Stanolind Oil and Gas Company. He is a member of the American Association of Petroleum Geologists, the American Geophysical Union, the American Mathematical Society, the American Physical Society, the Seismological Society of America, the Tulsa Geological Society, and the Society of Exploration Geophysicists.

PERSONAL ITEMS

(Members are requested to forward material for inclusion in PERSONAL ITEMS to J. F. Gallie, P. O. Box 2585, Houston, Texas)

SAM ZIMERMAN, Seismograph Party Chief with the Carter Oil Company, has advised the Society of his change of address to P. O. Box 887, Jackson, Mississippi.

L. J. PADDISON, of the Stanolind Oil and Gas Company, has been transferred from Andrews to P. O. Box 1088, Monahans, Texas.

LAVON C. DODD, formerly with the Sun Oil Company in Beaumont, Texas, is now an Electrical Design Engineer with the Lockheed Aircraft Corporation in Burbank, California. His home address is 505 Fairmont Avenue, Glendale, California.

FRANK F. LEHMAN, whose former address was c/o Mene Grande Seis., Aptdo. 45, Barcelona, Venezuela, has notified the Society of his change of address to P. O. Box 1413, Cristobal, Canal Zone.

E. T. NICHOLS, geologist with the California Company, has been transferred to the New Orleans offices of that company in the Canal Bank Building.

E. E. UNGER, of the Gulf Research and Development Company, notes his mailing address as being Box 1271, San Angelo, Texas.

MARTIN J. GOULD, formerly of the Geophysical Research Department of the Stanolind Oil and Gas Company, has been serving in the Naval Ordnance Laboratory, Navy Yard, Washington, D. C., since June 23rd of last year.

LT. G. W. HOSTETLER, formerly with the Petty Geophysical Engineering Company, may be reached at the Signal Corps School, Ft. Monmouth, Red Bank, N. J.

G. L. BARKSDALE, who was in the United States from February until November of 1941, has returned to South America, and may be addressed c/o Caribbean Petroleum Co., Maracaibo, Venezuela.

STEFAN VON CROY, of the Barnsdall Oil Company, has been transferred to Tulsa, Oklahoma, with the mailing address Box 2039.

R. H. WOODWARD, Research Associate at the Massachusetts Institute of Technology, has advised the Society of a change of address from Cambridge to 38 Orchard Street, Belmont, Mass.

R. L. AUGENTHALER, of the Standard Oil Co. of California, has the mailing address P. O. Box 930, Merced, California.

HORACE S. MOORE advised the Society late in November of his change of address, from Manila, Philippine Islands, to 647 Euclid Avenue, Los Angeles, California.

NEAL J. SMITH and J. W. HOOVER, formerly with the California Company in Houston, have been transferred to the New Orleans offices in the Canal Bank Building.

J. M. KENDALL is now an engineer in the Naval Ordnance Laboratory, Navy Yard, Washington, D. C. His home address is 1102 45th Place S. E., Washington, D. C.

DANIEL F. ELAM is serving as a Lieutenant in the Coast Artillery Corps of the U.S. Army at Ft. Crockett, Texas. His address in Galveston is 1811 32nd Street.

LAWRENCE A. GOEBEL, of the Carter Oil Co., has been transferred to P. O. Box 949, Decatur, Illinois.

JOHN H. HODGSON, engineer with the Schlumberger Well Surveying Corporation, may be addressed at P. O. Box 429, Houma, La.

W. A. MESZAROS should be addressed c/o M. G. O. Seismograph, Aptdo. 45, Barcelona, Venezuela, S. A.

W. B. WILEY, of the Gulf Research and Development Company, has been transferred from Columbia to P. O. Box 733, Laurel, Mississippi.

C. H. DRESBACH has advised the Society of his transfer from the Gulf Research and Development Company to the Western Gulf Oil Company, 1260 Subway Terminal Building, Los Angeles, California.

HARRY R. IMLE, formerly with the Carter Oil Company, is serving as a Lieutenant with Bat. C., 32nd Bn., Field Artillery Replacement Center, Ft. Sill, Oklahoma.

W. C. NORTHCUTT, Seismograph Party Chief with the Continental Oil Co., should be addressed at Box 146, Fresno, California.

LYNN G. HOWELL, formerly with the Humble Oil and Refining Co., is now with the Carnegie Institution of Washington, Dept. of Terrestrial Magnetism, Washington, D. C.

JACK F. JUDSON, Seismograph Party Chief with the Socony-Vacuum Oil Company, is located at 481 East Wapello Lane, Altadena, California.

Members in the Third Railroad Commission District, 8th Corps Area, of the Society of Exploration Geophysicists, the Houston Geological Society, the Gulf Coast Section of the A.I.M.M.E., and the Houston Chapter of the A.P.I., met jointly in the Lamar Hotel Ball Room, Fourth Floor, Wednesday, December 17, at 7:30 P.M., to discuss participation in various Civilian Defense measures. All members of these organizations in the Third Railroad Commission District have now been sent a detailed questionnaire by E. E. ROSAIRE, Temporary Personnel Chairman, and they are urgently requested to complete the form and to return it promptly. Members in this District who failed to receive their copy are requested to address Dr. Rosaire at P. O. Box 2545, Houston, Texas.

B. G. HUBNER, JR., of the National Geophysical Co., has been transferred from El Dorado to Magnolia, Arkansas.

LT. LEONARD F. UHRIG, formerly with the Shell Oil Co., Inc., is serving with the 21st Ordnance Bn., 5th Armored Division, Ft. Knox, Ky.

The Society has been advised of the change of address of WALTER D. BAIRD from Martinez, California, to P. O. Box 391, Fresno.

JOHN C. HOFFMAN, of the United Geophysical Co., has been transferred to Dickinson, North Dakota, with offices in the Liberty National Bank Building.

LT. JAMES B. BATSON, formerly with the Magnolia Petroleum Co., is serving with the 53rd Signal Battalion, Camp Bowie, Texas.

JAMES C. TEMPLETON, Managing Director of the Geophysical Prospecting Co., Ltd., of London, England, will be in South America for another three months, and should accordingly be addressed c/o Trinidad Petroleum Development Co., Ltd., Trinidad, B. W. I.

MAURICE SKLAR, of the Shell Oil Co., Inc., is now located in Big Lake, Texas, with the postal address Box 867.

MALVIN G. HOFFMAN has advised the Society that he is now located at 3821 W St., S. E. (Fairfax Village), Washington, D. C.

JOHN G. COOKE, JR., formerly with the Arkansas-Louisiana Gas Co., is serving as 1st Lt. A. C., Signal Officer, at the Greenville Air Corps Basic Flying School, Greenville, Miss. His mailing address is given as 303 Garrison St., Leland, Miss.

O. B. MANES resigned from the Independent Exploration Company last July 30th to accept employment with the Stanolind Oil and Gas Co., P. O. Box 728, Beeville, Texas.

The Director of the U. S. Waterways Experiment Station, P. O. Box 631, Vicksburg, Mississippi, has forwarded a recent News Letter to the Society, noting: "The purpose of this third issue of the Waterways Experiment Station News Letter is to acquaint Engineer Department offices and other interested agencies with the facilities of the Engineer Department Research Center's library, which is located at the Experiment Station. . . . Though intended primarily for use by the Engineer Department personnel, the Research Center's library will lend books to those individuals who are connected with reputable firms or institutions. Books may be obtained on a 30-day loan basis, and this time limit can usually be extended when necessary." The library is described as containing in excess of 10,000 items, including books and periodicals, technical reports, translations, microfilms, motion picture films and lantern slides, relating in the largest measure to hydraulics and soil mechanics; however, a wealth of material has been accumulated dealing with related sciences.

CAPTAIN JOHN G. KEARBY is in the Experimental Engineering Section, Wright Field, Dayton, Ohio. Upon being called to duty, he was placed in charge of the high altitude laboratory.

J. B. HERSEY is serving as a research worker in the Naval Ordnance Laboratory, Navy Yard, Washington, D. C. His mailing address is 1517 R St., N. W., Washington, D. C.

J. G. JEROME, formerly with Independent Exploration Co., is now with Seismic Explorations, Inc., 2911 Gulf Bldg., Houston, Texas.

B. M. BENCH should be addressed c/o V. G. Bench, 2305 70th St., Chicago, Illinois.

R. W. LINDSEY, of the Gulf Research and Development Company, has been transferred to Liberty, Texas, with the mailing address P. O. Box 191.

CHARLES A. DURHAM, formerly with the Humble Oil and Refining Company, is now with the International Petroleum Co., Ltd., Guayaquil, Ecuador, S. A.

JOHN S. IVY has his offices located at 1124 Neils Esperson Bldg., Houston, Texas.

FOREST F. LAMBRECHT, on leave from the Texas Company, is a student in the Officer Candidate School, E. S. S. C., Ft. Belvoir, Virginia.

FRANCIS A. ROBERTS has returned from the Netherlands East Indies and is in the Geophysical Department of the Carter Oil Co., Tulsa, Okla.

HARRISON E. STOMMEL, of the Magnolia Petroleum Co., should be addressed at 521 S. Whitcomb St., Ft. Collins, Colorado.

FRANCIS H. CADY, of the Carter Oil Co., has been transferred from Duncan to P. O. Box 552, Hobart, Oklahoma. This same change of address holds for G. C. HOWARD also.

LT. J. P. FARIS, JR., is on duty at Hicks Field, Ft. Worth, Texas.

WALTER E. MARTIN is in the U. S. Engineer Office, Geology Section, Little Rock, Arkansas.

RUSSELL C. DOOLITTLE should be addressed c/o F. W. Doolittle, 79 Brompton Road, Garden City, L. I., New York.

Because of the declaration of war against the United States in December, it was felt inadvisable to publish the annual membership list in the January issue of GEOPHYSICS, Volume VII, Number 1, for 1942. Instead, an attempt will be made to publish a more complete list and a more accurate one in the April issue. Society members will be furnished cards requesting specific information as to the nature of their employment, and they are requested to return them promptly in order that the information listed in the annual membership list may be as complete as possible.

STATEMENT OF THE OWNERSHIP, MANAGEMENT, CIRCULATION, ETC., REQUIRED BY THE ACTS OF CONGRESS OF AUGUST 24, 1912, AND MARCH 3, 1933

of GEOPHYSICS, published quarterly at Menasha, Wisconsin, for October, 1941.

State of Texas } ss
County of Harris }

Before me, a Notary Public in and for the State and county aforesaid, personally appeared J. F. Gallie, who, having been duly sworn according to law, deposes and says that he is the Business Manager of the Geophysics and that the following is, to the best of his knowledge and belief a true statement of the ownership, management (and if a daily paper, the circulation), etc., of the aforesaid publication for the date shown in the above caption, required by the Act of August 24, 1912, as amended by the Act of March 3, 1933, embodied in section 537. Postal Laws and Regulations, printed on the reverse of this form, to wit:

1. That the names and addresses of the publisher, editor, managing editor, and business managers are: Publisher, George Banta Publishing Company, Menasha, Wisconsin; Editor, R. D. Wyckoff, Box 2038, Pittsburgh, Pennsylvania; Managing Editor, R. D. Wyckoff, Box 2038, Pittsburgh, Pennsylvania; Business Manager, J. F. Gallie, Box 2585, Houston, Texas.

2. That the owner is (If owned by a corporation, its name and address must be stated and also immediately thereunder the names and addresses of stockholders owning or holding one per cent or more of total amount of stock. If not owned by a corporation, the names and addresses of the individual owners must be given. If owned by a firm, company, or other unincorporated concern its name and address, as well as those of each individual member, must be given.) Owned by The Society of Exploration Geophysicists, Executive Committee: President, H. B. Peacock, 821 Esperson Bldg., Houston Texas; Vice-President, F. Goldstone, Box 2099, Houston, Texas; Secretary-Treasurer, W. M. Rust Jr., Box 2180, Houston, Texas; Editor, R. D. Wyckoff, Box 2038, Pittsburgh, Pa.; Past President, W. T. Born, Box 2040, Tulsa, Oklahoma.

3. That the known bondholders, mortgagees, and other security holders owning or holding 1 per cent or more of total amount of bonds, mortgages, or other securities are: (If there are none, so state.) None; non-profit organization.

4. That the two paragraphs next above, giving the names of the owners, stockholders, and security holders, if any, contain not only the list of stockholders and security holders as they appear upon the books of the company but also, in cases where the stockholder or security holder appears upon the books of the company as trustee or in any other fiduciary relation, the name of the person or corporation for whom such trustee is acting, is given; also that the said two paragraphs contain statements embracing affiant's full knowledge and belief as to the circumstances and conditions under which stockholders and security holders who do not appear upon the books of the company as trustees, hold stock and securities in a capacity other than that of a bona fide owner; and this affiant has no reason to believe that any other person, association, or corporation has any interest direct or indirect in the said stock, bonds, or other securities than as so stated by him.

5. That the average number of copies of each issue of this publication sold or distributed, through the mails or otherwise, to paid subscribers during the twelve months preceding the date shown above is not daily. (This information is required from daily publications only.)

J. F. GALLIE

Sworn to and subscribed before me this 27th day of January, 1942.

[SEAL] J. M. BUSH

(My commission expires June 1, 1943.)